ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
DOI: 10.17559/TV-20160216023828

CHARACTERISTICS OF BURIED PALEO-CHANNELS IN THE WESTERN SOUTH YELLOW SEA DURING THE LATE LAST GLACIATION

Zhaojun Song, Jianping Li, Zhenkui Gu, Wenjia Tang, Jifeng Yu, Luo Gao

Original scientific paper
Studies on the evolution of paleo-channels in coastal areas are important for submarine engineering construction and to reveal changes in the global paleoenvironment. Thus, to explore the characteristics of paleo-channels during the late Last Glaciation in the western South Yellow Sea, digital terrain analysis method and ArcGis river extraction function were employed, high-resolution shallow stratigraphic seismic profiles and core data were analysed, and river empirical formulas were used to determine river properties and river patterns. Results indicate that the ancient river system during the late Last Glaciation of the South Yellow Sea shelf is divided into paleo-Yellow (Huanghe) and paleo-Yangtze (Changjiang) Rivers. The paleo-channels near 33°N belong to the paleo-Yangtze River, and generally flow from east to northeast. The paleo-channels around 35°N and 123,5°E are part of the paleo-Yellow River. Compared with the paleo-Yellow River, the paleo-Yangtze River is prone to horizontal migration and has higher penetration depths and discharge. Based on the slope-width method, the paleo-Yellow River system can be considered mainly as a meandering river, whereas the paleo-Yangtze River system is largely a braided river. Remarkable differences are found between the paleo-Yangtze River and the paleo-Yellow River. The characteristics of buried paleo-channels during the late Last Glaciation can be useful in predicting the incident potential hazard of submarine engineering and in revealing the paleoenvironment changes in the South Yellow Sea shelf.

Keywords: *buried paleo-channels; paleo-Yellow River; paleo-Yangtze River; submarine engineering; western South Yellow Sea*

Značajke podzemnih paleolitskih korita u zapadnom Južnom Žutom moru tijekom kasnog posljednjeg ledenog doba

Izvorni znanstveni članak
Istraživanja o evoluciji paleolitskih korita u obalnim područjima važna su za konstrukcije podmorskog inženjerstva i za otkrivanje promjena u globalnom paleolitskom okruženju. Stoga je za istraživanje značajki paleo-korita tijekom kasnog posljednjeg ledenog doba u zapadnom Južnom Žutom moru primijenjena digitalna metoda analize terena i ArcGis funkcija porijekla rijeke, analizirani su plitki stratigrafski seizmički profili visoke rezolucije i osnovni podaci, a rabljene su empirijske formule rijeke za određivanje riječnih svojstava i struktura. Rezultati pokazuju da je drevni riječni sustav tijekom kasnog posljednjeg ledenog doba grebena Južnog Žutog mora podijeljen na paleo-Žutu (Huanghe) i paleo-Yangtze (Changjiang) rijeku. Paleo-korita blizu 33°N pripadaju paleo-Yangtze rijeci i uglavnom teku od istoka do sjeveroistoka. Paleo-korita oko 35°N i 123,5°E dio su paleo-Žute rijeke. U usporedbi s paleo-Žutom rijekom, paleo-Yangtze rijeka inklinira horizontalnom premiještanju, ima veću prodornu moć i veću količinu vode. Na temelju metode širine nagiba sustav paleo-Žute rijeke može se smatrati uglavnom krivudavim dok je sustav paleo-Yangtze rijeke uglavnom sustav račvaste (braided) rijeke. Pronađene su značajne razlike između paleo-Yangtze rijeke i paleo-Žute rijeke. Značajke podzemnih paleo-korita tijekom kasnog posljednjeg ledenog doba mogu biti korisne u predviđanju popratne moguće opasnosti kod podvodnih konstrukcija i otkrivanju promjena paleookruženja u grebenu Južnog Žutog mora.

Ključne riječi: *paleo-Žuta rijeka; paleo-Yangtze rijeka; podmorsko inženjerstvo; podzemna paleo-korita; zapadno Južno Žuto more*

1 Introduction

Since the late Pleistocene era, global sea levels have experienced several fluctuations; the Yellow Sea and the East China Sea also went through several large-scale transgressions and regressions [1÷3]. During the periods of low sea level, the rivers, deltas, lakes, marshes, and other landscape units developed upon the bare shelves of the Yellow Sea and the East China Sea. As the sea level rose, these units became buried sedimentary bodies. In sea areas with smaller deposition rates, the sedimentary bodies can preserve their original features to different extents, which can be identified from the shallow stratigraphic seismic profiles [4÷7]. The buried sedimentary bodies are considered as adverse geological conditions for submarine engineering, because they may inflict direct harm or have potential effect on submarine engineering construction [8÷10]. The buried paleo-channels are also the product of climate and geological changes, and record abundant geological information during environment changes [11÷13]. During the low sea level in the Last Glaciation, the Yellow (Huanghe) and the Yangtze (Changjiang) Rivers joined at the northern Jiangsu Province, and flowed into the Yellow Sea basin [14, 15]. This phenomenon significantly influenced the paleoenvironment of Yellow Sea. However, the characteristics of these paleo-channels on the shelf of the South Yellow Sea remain unclear.

2 State of the art

In the past two decades, considerable efforts have been exerted to study the buried channel systems on the continental shelf of the South Yellow Sea. Li et al. [16] discussed the distribution of buried paleo-channels and to which river system they belong. Gu et al. [17] identified the types, seismic stratigraphy, and sedimentary character of paleo-channel cross-section by conducting a synthetic study on seismic facies and core data. Kong et al. [3] revealed the seismic geomorphology of buried channel systems in the western South Huanghai Sea. Liu et al. [18] discussed the effects of buried channel systems on submarine engineering construction in the coastal and offshore areas of the Yellow River delta. Although several studies have been conducted, the flow path of paleo-Yellow River and paleo-Yangtze River remain controversial. Li et al. [16] proposed that the paleo-Yellow River system flowed from the northwest to the southeast during the late Pleistocene era, whereas the paleo-Yangtze River ran from the southwest to the northeast; they also argued that the two river systems converged in the mid-eastern regions in the South Yellow Sea. Yang et al. [19] suggested that the paleo-Yangtze

River extended in the northern and eastern directions from Jianggang Region in Northern Jiangsu Province during the Last Glaciation. Gu et al. [17] viewed the paleo-Yellow River and paleo-Yangtze River in the Last Glaciation as two separate river systems in the north and the south.

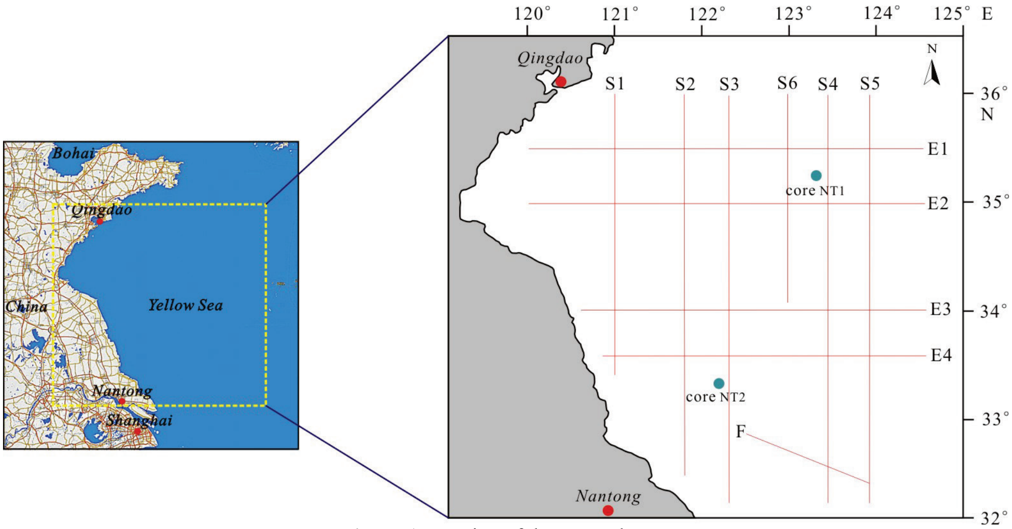

Figure 1 Location of the research area

Previous studies have also suggested that buried paleo-channels of the Yellow River, the Yangtze River, and the Pearl River had been found in the Bohai Sea, the East China Sea, and the South China Sea, respectively. During the Last Glaciation, China's two largest rivers, the Yellow River and the Yangtze River, had converged at Northern Jiangsu and flowed into the South Yellow Sea for a long time. Paleo-deltas and buried paleo-channels were superposed upon the South Yellow Sea shelf beyond the shore of Northern Jiangsu. This complex situation is well recorded on a large number of the shallow stratigraphic seismic profiles [3, 17, 20, 21]. These paleo-channels were formed from either the Yellow River or the Yangtze River. In terms of the origin or structure, these paleo-channels are more complex than those of the East China Sea and the South China Sea. However, relevant studies on these paleo-channels remain not enough. Thus, the distribution and characteristics of paleo-channels in the western South Yellow Sea during the late Last Glaciation were analysed in the present study.

The rest of this paper is organized as follows. Section 3 describes the data sources and processing methods. Section 4 presents the distribution of paleo-channels based on the interpretation of shallow stratigraphic seismic profiles, as well as the river patterns and paleo-channel properties using river empirical formulas. Conclusions are provided in Section 5.

3 Methodology

Seismic and geological shallow drilling surveys (cores Nantong 1 [NT1] and Nantong 2 [NT2]) were conducted during the geological survey project on South Yellow Sea in 2002. Approximately 3000 km of high-resolution shallow stratigraphic seismic profiles were acquired using the Delph seismic system for data acquisition (Figure 1). The thickness of the reflection in the profile was calculated using the acoustic velocity of 1650 m/s following Liu et al. [22] Interpretation of the seismic data was based on the recognition of minor seismic discontinuities by comparing seismic facies with lithofacies of cores NT1 and NT2.

Around 3000 km of shallow stratigraphic seismic profiles (Fig. 1) were used to study the buried paleo-channels in the South Yellow Sea, and numerous paleo-channels during the Last Glaciation were found by interpreting these profiles. The internal sediments in river cross-sections are characterized largely by chaotic and irregular reflections (Fig. 2). Mathematical statistics on the cross-section parameters of the paleo-channels during the Last Glaciation in seismic profiles were performed to investigate the river characteristics and their horizontal distribution. Hundreds of typical parameters of paleo-channel cross-section were sorted out, such as azimuth of extended cross-section, cross-section trend (i.e., paleo-channel direction), valley depth and valley width, etc. Finally, a total of 93 clear, and typical cross-sections were selected (Tab. 1), and those lying above the QS2-0 unconformity were continental strata in the late Last Glaciation. The various parameters of paleo-channel cross-sections are summarized in Table 1, of which the valley width refers to the width of valley shoulder, and the valley depth is the vertical distance from valley shoulder to valley bottom. Other parameters were calculated according to empirical formulas (1)÷(6) [23].

$$f = w/d = 225c^{-1{,}08}. \tag{1}$$

$$p = 3{,}5 f^{-0{,}27}. \tag{2}$$

$$\lg s = 1{,}480585 + 0{,}94774 \cdot \lg f - 0{,}87937 \cdot \lg w. \tag{3}$$

$$\lg l = 1{,}27809 + 0{,}52822 \cdot \lg f + 0{,}68744 \cdot \lg w. \tag{4}$$

$$\lg q = -1{,}24661 - 1{,}13327 \cdot \lg f + 2{,}42853 \cdot \lg w. \tag{5}$$

$$S_v = sp. \tag{6}$$

In these formulas, f refers to the width-to-depth ratio of paleo-channel; c is the content of suspended matter; p is the river-bend curvature; s is the riverbed slope; l is the meander wavelength; q is the average discharge (m^3/s); S_v is the slope at the paleo-channel bottom; d is the valley depth; and w is the valley width.

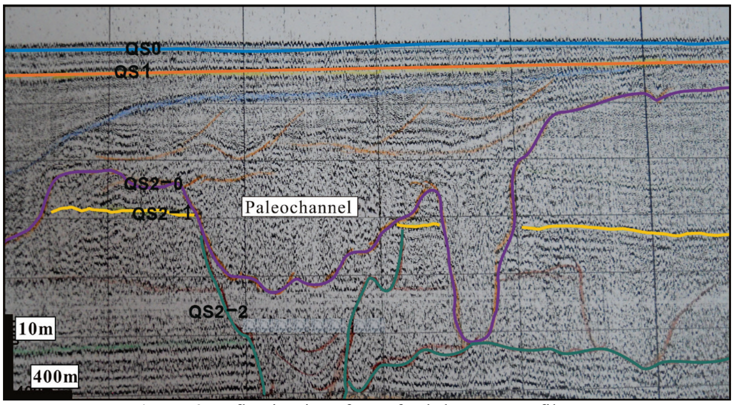

Figure 2 Reflecting interface of sub-bottom profile

QS0: Seabed reflecting interface; QS1: Marine strata bottom interface during the Holocene stage; QS2-0: Continental strata bottom interface during the late Last Glaciation; QS2-1: Marine strata bottom interface during the Last Glaciation; QS2-2: Continental strata bottom interface during the early Last Glaciation.

Table 1 Characteristic parameters of paleo-channel cross-sections

No.	w (m)	d (m)	f	lg f	lg w	lg s	lg l	lg q	S×10^{-3}	p	S_v	c (%)
1	264	16	16,5	1,22	2,42	0,51	3,59	3,25	0,61	1,64	1,00	11,22
2	584	27	21,5	1,33	2,77	0,31	3,89	3,97	0,39	1,53	0,60	8,80
3	348	8	45,8	1,66	2,54	0,82	3,90	3,04	0,13	1,25	0,16	4,37
4	278	12	22,4	1,35	2,44	0,61	3,67	3,15	0,77	1,51	1,16	8,45
5	490	26	18,8	1,27	2,69	0,32	3,80	3,85	0,40	1,58	0,63	9,94
6	629	24	26,2	1,42	2,80	0,36	3,95	3,94	0,44	1,45	0,64	7,32
7	400	16	25,0	1,40	2,60	0,52	3,81	3,48	0,62	1,47	0,91	7,65
8	300	8	35,7	1,55	2,48	0,77	3,80	3,02	1,13	1,33	1,50	5,50
9	350	9	38,0	1,58	2,54	0,74	3,86	3,13	1,04	1,31	1,36	5,18
10	200	18	10,9	1,04	2,30	0,44	3,41	3,16	0,52	1,84	0,96	16,54
11	600	25	24,0	1,38	2,78	0,34	3,92	3,94	0,42	1,48	0,62	7,94
12	100	8	12,5	1,10	2,00	0,76	3,23	2,36	1,09	1,77	1,93	14,53
13	80	7	11,8	1,07	1,90	0,82	3,15	2,15	1,26	1,80	2,27	15,37
14	300	12	25,0	1,40	2,48	0,63	3,72	3,19	0,80	1,47	1,18	7,65
15	300	10	30,0	1,48	2,48	0,70	3,77	3,10	0,95	1,40	1,33	6,46
16	207	8	25,9	1,41	2,32	0,78	3,62	2,79	1,15	1,45	1,67	7,41
17	207	8	25,9	1,41	2,32	0,78	3,62	2,79	1,15	1,45	1,67	7,41
18	317	9	37,3	1,57	2,50	0,77	3,83	3,05	1,12	1,32	1,48	5,28
19	303	10	29,2	1,47	2,48	0,69	3,76	3,11	0,92	1,41	1,30	6,63
20	179	10	17,9	1,25	2,25	0,69	3,49	2,80	0,92	1,61	1,48	10,40
21	821	20	41,0	1,61	2,91	0,45	4,13	4,00	0,53	1,28	0,68	4,83
22	301	10	30,1	1,48	2,48	0,70	3,77	3,10	0,96	1,40	1,34	6,44
23	137	12	11,4	1,06	2,14	0,60	3,31	2,75	0,76	1,81	1,38	15,83
24	274	12	22,8	1,36	2,44	0,62	3,67	3,14	0,80	1,50	1,20	8,33
25	274	14	19,5	1,29	2,44	0,56	3,64	3,22	0,69	1,57	1,08	9,61
26	342	16	21,4	1,33	2,53	0,52	3,72	3,39	0,62	1,53	0,95	8,85
27	267	12	22,2	1,35	2,43	0,62	3,66	3,12	0,80	1,52	1,22	8,53
28	60	4	15,0	1,18	1,78	1,03	3,13	1,74	2,04	1,68	3,43	12,27
29	70	6	11,7	1,07	1,85	0,87	3,12	2,03	1,40	1,80	2,52	15,49
30	60	6	10,0	1,00	1,78	0,86	3,03	1,94	1,39	1,88	2,61	17,87
31	73	6	12,2	1,09	1,86	0,88	3,13	2,04	1,41	1,78	2,51	14,90
32	150	8	18,8	1,27	2,18	0,77	3,45	2,61	1,13	1,59	1,80	9,98
33	293	18	16,3	1,21	2,47	0,46	3,62	3,38	0,55	1,65	0,91	11,37
34	293	10	29,3	1,47	2,47	0,70	3,75	3,09	0,95	1,41	1,34	6,60
35	120	5	24,0	1,38	2,08	0,96	3,44	2,24	1,73	1,48	2,56	7,94
36	333	15	22,2	1,35	2,52	0,54	3,72	3,34	0,65	1,52	0,99	8,53
37	160	8	20,0	1,30	2,20	0,78	3,48	2,62	1,13	1,56	1,76	9,41
38	160	10	16,0	1,20	2,20	0,68	3,42	2,74	0,91	1,66	1,51	11,56
39	467	20	23,3	1,37	2,67	0,43	3,84	3,68	0,51	1,50	0,77	8,15
40	99	8	11,9	1,08	2,00	0,75	3,22	2,39	1,06	1,79	1,90	15,18
41	267	10	26,7	1,43	2,43	0,70	3,70	3,03	0,95	1,44	1,37	7,21
42	400	12	33,3	1,52	2,60	0,64	3,87	3,34	0,82	1,36	1,12	5,86

Table 1 Characteristic parameters of paleo-channel cross-sections (continuation)

No.	w (m)	d (m)	f	lg f	lg w	lg s	lg l	lg q	$S\times10^{-3}$	p	S_v	c (%)
43	133	8	16,7	1,22	2,12	0,77	3,38	2,52	1,12	1,64	1,84	11,14
44	205	16	12,8	1,11	2,31	0,50	3,45	3,11	0,60	1,76	1,06	14,19
45	137	8	17,1	1,23	2,14	0,76	3,40	2,56	1,12	1,63	1,83	10,88
46	205	16	12,8	1,11	2,31	0,50	3,45	3,11	0,60	1,76	1,06	14,19
47	205	14	14,7	1,17	2,31	0,56	3,48	3,04	0,68	1,70	1,16	12,54
48	895	30	30,1	1,48	2,95	0,29	4,09	4,24	0,37	1,4	0,52	6,44
49	694	62	11,2	1,05	2,84	−0,02	3,79	4,46	0,18	1,82	0,33	16,11
50	971	68	14,3	1,15	2,99	−0,05	3,94	4,71	0,17	1,71	0,29	12,84
51	1572	61	25,7	1,41	3,2	0,01	4,22	4,93	0,19	1,46	0,28	7,46
52	1202	32	37,2	1,57	3,08	0,26	4,23	4,45	0,35	1,32	0,46	5,29
53	601	30	20,2	1,31	2,78	0,27	3,88	4,02	0,36	1,55	0,56	9,31
54	1202	94	12,9	1,11	3,08	−0,18	3,98	4,98	0,13	1,76	0,23	14,15
55	1017	77	13,3	1,12	3,01	−0,1	3,94	4,79	0,15	1,74	0,26	13,72
56	1300	26	51,0	1,71	3,11	0,36	4,32	4,37	0,43	1,21	0,52	3,95
57	1157	34	34,0	1,53	3,06	0,24	4,19	4,45	0,33	1,35	0,45	5,75
58	1571	40	39,3	1,59	3,2	0,18	4,32	4,72	0,29	1,3	0,38	5,03
59	2286	29	79,1	1,9	3,36	0,33	4,59	4,76	0,4	1,08	0,43	2,63
60	2238	51	43,9	1,64	3,35	0,09	4,45	5,03	0,23	1,26	0,29	4,54
61	1399	60	23,5	1,37	3,15	0,01	4,17	4,85	0,2	1,49	0,30	8,1
62	1708	72	23,6	1,37	3,23	−0,06	4,22	5,04	0,17	1,49	0,25	8,06
63	1258	34	37,0	1,57	3,1	0,24	4,24	4,50	0,33	1,32	0,44	5,32
64	1882	68	27,7	1,44	3,27	−0,03	4,29	5,06	0,18	1,43	0,26	6,96
65	941	69	13,7	1,14	2,97	−0,06	3,92	4,67	0,17	1,73	0,29	13,38
66	800	21	37,7	1,58	2,9	0,42	4,11	4,01	0,5	1,31	0,66	5,24
67	847	43	19,5	1,29	2,93	0,13	3,97	4,41	0,26	1,57	0,41	9,61
68	1182	51	23,2	1,36	3,07	0,07	4,11	4,67	0,22	1,5	0,33	8,21
69	636	8	83,7	1,92	2,8	0,84	4,22	3,38	1,3	1,06	1,38	2,5
70	533	43	12,6	1,1	2,73	0,12	3,74	4,14	0,25	1,77	0,44	14,48
71	889	38	23,2	1,37	2,95	0,18	4,03	4,36	0,29	1,5	0,44	8,18
72	800	77	10,5	1,02	2,9	−0,11	3,81	4,64	0,15	1,86	0,28	17,14
73	1733	21	81,6	1,91	3,24	0,44	4,52	4,46	0,53	1,07	0,57	2,56
74	6000	68	88,3	1,95	3,78	0	4,91	5,72	0,19	1,04	0,20	2,38
75	2444	77	32,0	1,5	3,39	−0,07	4,40	5,29	0,16	1,37	0,22	6,09
76	1189	27	43,7	1,64	3,08	0,33	4,26	4,37	0,41	1,26	0,52	4,56
77	1166	37	31,9	1,5	3,07	0,21	4,18	4,51	0,31	1,37	0,42	6,1
78	2629	21	123,7	2,09	3,42	0,46	4,73	4,69	0,54	0,95	0,51	1,74
79	1600	17	94,1	1,97	3,2	0,53	4,52	4,29	0,65	1,03	0,67	2,24
80	467	43	11,0	1,04	2,67	0,12	3,66	4,06	0,25	1,83	0,46	16,39
81	1133	68	16,7	1,22	3,05	−0,05	4,02	4,78	0,17	1,64	0,28	11,14
82	3866	43	91,0	1,96	3,59	0,18	4,78	5,25	0,29	1,04	0,30	2,31
83	2599	34	76,5	1,88	3,41	0,26	4,62	4,90	0,35	1,09	0,38	2,72
84	933	47	20,0	1,3	2,97	0,1	4,01	4,49	0,24	1,56	0,37	9,42
85	1266	47	27,1	1,43	3,1	0,11	4,17	4,66	0,24	1,44	0,35	7,1
86	1528	17	89,9	1,95	3,18	0,53	4,50	4,27	0,65	1,04	0,68	2,34
87	494	47	10,6	1,02	2,69	0,08	3,67	4,13	0,23	1,85	0,43	16,96
88	899	30	30,2	1,48	2,95	0,29	4,09	4,24	0,37	1,39	0,51	6,42
89	1618	34	47,6	1,68	3,21	0,25	4,37	4,65	0,34	1,23	0,42	4,21
90	1422	43	33,5	1,52	3,15	0,15	4,25	4,68	0,27	1,36	0,37	5,84
91	584	17	34,4	1,54	2,77	0,5	4,00	3,74	0,6	1,35	0,81	5,7
92	809	17	47,6	1,68	2,91	0,51	4,17	3,92	0,62	1,23	0,76	4,21
93	497	9	58,4	1,77	2,7	0,78	4,07	3,30	1,15	1,17	1,35	3,49

4 Result analysis and discussion

4.1 Distribution of paleo-channels

Based on the paleotopography recovery and digital terrain analysis [15] and the location of paleo-channels reflected on the shallow stratigraphic seismic profiles, we extracted the horizontal distribution characteristics of paleo-channels in western South Yellow Sea during the late Last Glaciation. The results show that in the late Last Glaciation, three main paleo-channels had developed in the western South Yellow Sea: near 33°N, the ancient river system generally flowed from east to northeast; close to 35°N, the main stream of paleo-channels flowed from east to southeast; and near 123,5°E, the entire paleo-channels flowed southeast (Fig. 3).

The results of provenance analysis of sediments from cores NT1 and NT2 [24÷26] are as follows: for Core NT2, the sediments from the upper section at 5,50÷19,40 m are mainly from the Yangtze River, which correspond to the continental sedimentation during periods of low sea level in the late Last Glaciation; for Core NT1, the sediments from the upper section at 7,70÷16,60 m are mainly from the Yellow River, which correspond to the continental sedimentation at the same period.

Based on the locations of the ancient river system and the data from the core sediments, the paleo-channels upon the South Yellow Sea shelf during the late Last Glaciation can be divided into paleo-Yangtze River and paleo-Yellow River (Figure 3). The paleo-channel close to 33°N is the paleo-Yangtze River system, which generally swept from east to northeast. The flow path of paleo- Yellow River might include the west (around 35°N) and north lines (around 123,5°E). In particular, near 35°N, the paleo-Yellow River system flowed from east to southeast, which affected the middle of the South Yellow Sea where Core NT1 locates. This river system then assembled with the north lines of the paleo-Yellow River system and turned to southeast direction.

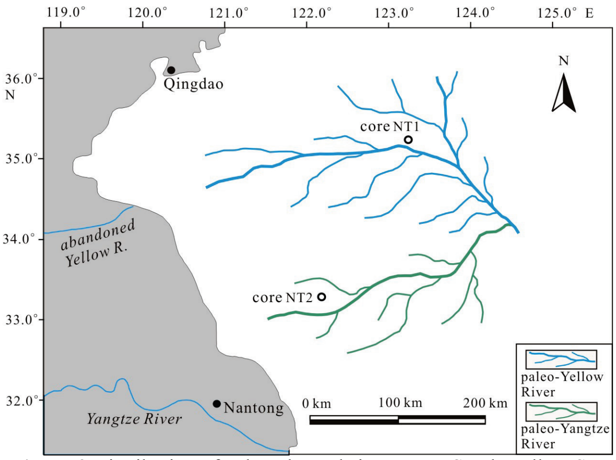

Figure 3 Distribution of paleo-channels in western South Yellow Sea during the Last Glaciation

4.2 Characteristics of paleo-channels

Among the several thousand kilometres of high-resolution shallow stratigraphic seismic profiles, more than 90 paleo-channel cross-sections with clear reflection characteristics were selected. We then recorded the coordinates of central points of the cross-sections and the morphological parameters of paleo-channels, including valley width and penetration depth. The relevant parameters (Tab. 1) were calculated based on the riverbed slope formula [27], and thus, the river patterns and river characteristics of paleo-channels were determined.

4.2.1 Paleo-channel property

The cross-section width and depth and other parameters of the paleo-Yellow River system and the paleo-Yangtze River system are listed in Tab. 1, including width-to-depth ratio, river-bend curvature, and content of suspended matter (Note: No. 1 ÷ No. 47 and No. 48 ÷ No. 93 are the characteristic parameters of the cross-sections of paleo-Yellow River and paleo-Yangtze River, respectively).

(1) Width-to-depth ratio (f) indicates the stability of paleo-channels during their development. The stability of the paleo-channel decreased with the increase of width-to-depth ratio. In this study, the average width-to-depth ratio of the paleo-Yellow River cross-section was 22,0, whereas that of the paleo-Yangtze River cross-section reached 39,9.

(2) Penetration depth, or the so-called river depth, is the vertical distance from the valley shoulder to valley bottom. The average penetration depth of the paleo-Yellow River was 12,26 m, while the maximum was 25 m. The average penetration depth of the paleo-Yangtze River was 42,96 m, with the maximum reaching 93,5 m. The paleo-Yangtze River had an obviously higher penetration depth.

(3) The discharge of paleo-channels can be calculated according to the empirical formula (5) summarized from modern discharge, i.e., $\lg q = -1{,}24661 - 1{,}13327 \cdot \lg f + 2{,}42853 \cdot \lg w$, where f is the width-to-depth ratio of river, w is the valley width, and q is the discharge (m^3/s). As shown in Table 3, the average width of the paleo-Yellow River was 270 m, and the average discharge q was 460 m^3/s. The average width of the paleo-Yangtze River was 650 m, and the average discharge q was 730 m^3/s. This finding indicates that the discharge of the paleo-Yangtze River is higher than that of the paleo-Yellow River.

4.2.2 River pattern

The river patterns of the paleo-channels in the western South Yellow Sea were determined by the slope-width method [27]. The primary parameters are discharge, slope, and valley width. Slope can reflect the sediment transportation characteristics of a river. Gravel riverbed is dominated by bed load transportation, whereas sandy riverbed is dominated by suspended load transportation. Under the same conditions, both the strength of bed load transportation and the slope of the braided river are higher than those of the meandering river. Valley width reflects the erosion and circulation distribution pattern of river. Given a constant discharge, the wider river tends to form a braided river, whereas the narrower one is more likely to form a meandering river [27]. The judgment formula based on slope-width method is composed of the empirical formulas (1), (2) and (3).

Using the formulas (1), (2) and (3), the suspended sand content, river-bend curvature, and vertical slope of the paleo-Yellow River and the paleo-Yangtze River were calculated (Tab. 1). Figs. 4 and 5 were plotted according to slope and valley width of the two paleo-channels. The boundary between meandering river and braided river is $s = 2{,}54 w^{-1{,}44}$, and that between gravel riverbed and sandy riverbed is $s = 0{,}0019 w^{-0{,}25}$. The results show that the gravel riverbed dominated the paleo-Yellow River, where the braided river accounted for 40 % and the meandering river for 60 %. Sandy riverbed dominated the paleo-Yangtze River, where the braided river accounted for 59,6 % and the meandering river for 40,4 %.

A considerable number of studies have shown that the Yangtze River and the Yellow River, as the two largest rivers in China, have significant differences in terms of geological background, hydrology conditions, geomorphology, and sedimentary characteristics. The Yangtze River is characterized by more water, less sand, fine material, more stable, and contains extremely diverse rock types in the basin. On the contrary, the Yellow River has less water, more sand, fine material, easy swing, and relatively simple rock types within the basin. These differences result in the obvious distinction in pattern and property between the two rivers. In the late period of the Last Glaciation, the paleo-Yangtze River had higher width-to-depth ratio at river cross-section than the paleo-Yellow River. Therefore, the riverbed location of paleo-Yangtze River is unstable and has the characteristics of lateral migration. This finding is similar to research findings on buried ancient channels in the continental shelf area out of the mouth of the Yangtze River [27]. According to the judgment of the slope-width method, the paleo-Yellow River system is dominated mainly by meandering rivers. This result is consistent with the results of a study on paleo-channel in the western South Yellow Sea (near the abandoned Yellow River Delta) [16]. However, the paleo-Yangtze River system is composed of braided rivers. This conclusion agrees well with the conclusions obtained by previous research on buried paleo-channels in the inner continental shelf out of the Yangtze River [27].

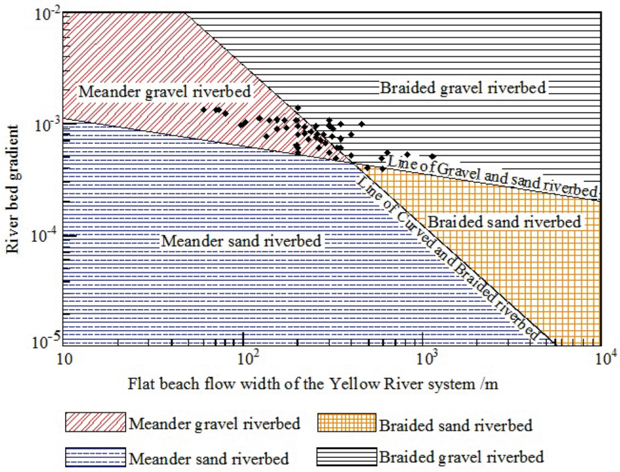

Figure 4 Judgment of riverbed type of the paleo-Yellow River based on slope-width method

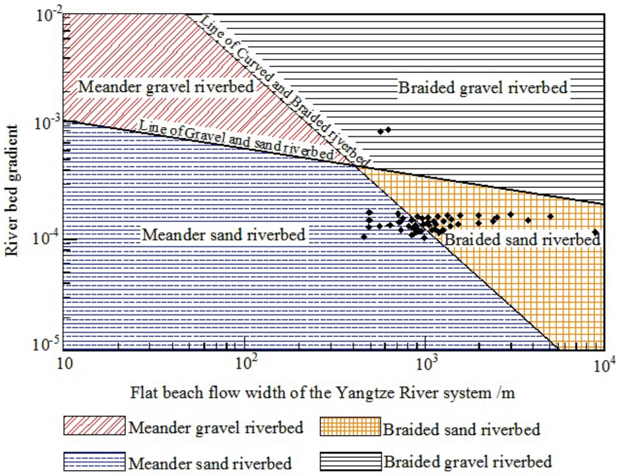

Figure 5 Judgment of riverbed type of the paleo-Yangtze River based on slope-width method

5 Conclusion

Interpretation of the high-resolution seismic profiles indicates that the two paleo-channel systems developed during the Last Glaciation on the shelf of the western South Yellow Sea. Using the estimated paleo-hydrologic parameters and the slope-width method, the properties of paleo-channels are determined. The main conclusions are summarized as follows:

During the late Last Glaciation, numerous paleo-channels developed upon the western South Yellow Sea shelf. According to their locations and core sediments, the paleo-channels are divided into paleo-Yangtze River system and paleo-Yellow River system. The paleo-channels near 33°N belong to the paleo-Yangtze River system, which generally swept from east to northeast. And the paleo-channels close to 35°N and 123,5°E are considered to be the two flow paths of paleo-Yellow River system.

Compared with the paleo-Yellow River, the paleo-Yangtze River is prone to horizontal migration and has higher penetration depth and discharge. The bottom of paleo-Yellow River is steeper than that of the paleo-Yangtze River. The average discharge of the paleo-Yellow River is 460 m^3/s, and that of the paleo-Yangtze River is 730 m^3/s. Therefore, the discharge of the paleo-Yangtze River is higher than that of the paleo-Yellow River.

By employing the slope-width method, the paleo-Yellow River system is determined to be composed mainly of meandering rivers with gravel riverbed, whereas the paleo-Yangtze River system is dominated by braided rivers with sandy riverbed.

Abundant oil and gas resources are found on the continental shelf of the South Yellow Sea, indicating its significant development potential. The buried paleo-channels are widely distributed in this area as geologic factors of the unstable seafloor and as parts of the latent disastrous types. These buried paleo-channels have a significant effect on the development of oil and gas resources. The results obtained in this study provide basic geological data of submarine engineering on the Southern Yellow Sea shelf. The details of the effects of the buried paleo-channels on submarine engineering should be considered in future extensions of this study.

Acknowledgement

This work was financially supported by the National Natural Science Foundation of China (NSFC) (41106036, 41472155) and Research Foundation of Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Minerals (DMSM201410).

6 References

[1] Liu, S. H.; Feng, A. P.; Du, J.; Xia, D. X.; Li, P.; Xue, Z.; Hu, W. F.; Yu, X. X. Evolution of the buried channel systems under the modern Yellow River Delta since the Last Glacial Maximum. // Quaternary International. 349, (2014), pp. 327-338. DOI: 10.1016/j.quaint.2014.06.061

[2] Wang, Z. B.; Yang, S. Y.; Zhang, Z. X.; Lan, X. H.; Gu, Z. F.; Zhang, X. H. Paleo-fluvial sedimentation on the outer shelf of the East China Sea during the last glacial maximum. // Chinese Journal of Oceanology and Limnology. 31, 4(2013), pp. 886-894. DOI: 10.1007/s00343-013-2253-5

[3] Kong, X. H.; Liu, J.; Du, Y. S.; Wen, C.; Xu, G. Seismic geomorphology of buried channel systems in the western South Huanghai Sea: retrodiction for paleoenvironments. //

Acta Oceanologica Sinica. 30, 1(2011), pp. 47-58. DOI: 10.1007/s13131-011-0090-y
[4] Lopes, R. P.; Buchmann, F. S. Pleistocene mammals from the southern Brazilian continental shelf. // Journal of South American Earth Sciences. 31, 1(2011), pp. 17-27. DOI: 10.1016/j.jsames.2010.11.003
[5] Samadder, R. K.; Kumar, S.; Gupta, R. P. Paleochannels and their potential for artificial groundwater recharge in the western Ganga plains. // Journal of Hydrology. 400, 1-2(2011), pp. 154-164. DOI: 10.1016/j.jhydrol.2011.01.039
[6] Zaleha, M. J. Paleochannel hydraulics, geometries, and associated alluvial architecture of Early Cretaceous rivers, Sevier Foreland Basin, Wyoming, USA. // Cretaceous Research. 45, (2013), pp. 321-341. DOI: 10.1016/j.cretres.2013.06.003
[7] Lantzsch, H.; Hanebuth, T. J. J.; Chiessi, C. M.; Schwenk, T.; Violante, R. A. The high-supply, current-dominated continental margin of southeastern South America during the late Quaternary. // Quaternary Research (United States). 81, 2(2014), pp. 339-354. DOI: 10.1016/j.yqres.2014.01.003
[8] Khan, Z. A.; Tewari, R. C. Paleochannel and paleohydrology of a Middle Siwalik (Pliocene) fluvial system, northern India. // Journal of Earth System Science. 120, 3(2011), pp. 531-543. DOI: 10.1007/s12040-011-0083-4
[9] Karmanov, V. N.; Chernov, A. V.; Zaretskaya, N. E.; Panin, A. V.; Volokitin, A. V. Paleochannel studies in archaeology: the case of the Vychegda River, Northeastern European Russia. // Archaeology, Ethnology & Anthropology of Eurasia. 41, 2(2013), pp. 83-93. DOI: 10.1016/j.aeae.2013.11.008
[10] Ambrosimov, A. K. On the discharge of bottom waters of the Northern Caspian into Derbent Depression through paleochannels. // Water Resources, 42, 4(2015), pp. 432-437. DOI: 10.1134/S0097807815040028
[11] Bellec, V. K.; Cirac, P.; Faugères, J. C. Formation and evolution of paleo-valleys linked to a subsiding canyon, North Aquitaine shelf (France). // Comptes Rendus Geoscience. 341, 1(2009), pp. 36-48. DOI: 10.1016/j.crte.2008.07.016
[12] Lazarus, E. D.; Murray, A. B. An integrated hypothesis for regional patterns of shoreline change along the Northern North Carolina Outer Banks, USA. // Marine Geology. 281, 1-4(2011), pp. 85-90.
[13] Wei, X.; Wu, C. Y. Holocene delta evolution and sequence stratigraphy of the Pearl River Delta in South China. // Science China Earth Sciences. 54, 10(2011), pp. 1523-1541. DOI: 10.1007/s11430-011-4238-6
[14] Li, F. J.; Li, L.; Lin, H.; Yang, Y. C.; Fang, C. G.; Meng, L. N. Distribution characteristics and controlling factors analyses on incised paleochannel reservoir of valley filling in Jurassic of Wuqi Area, Ordos Basin. // Natural Gas Geoscience. 24, 6(2013), pp. 1109-1117.
[15] Song, Z. J.; Gu, Z. K.; Gao, L.; Guo, D. W. Paleochannel distribution on South Yellow Sea shelf in late Wurm Glacial based on ArcGis. // International Journal of Earth Sciences and Engineering. 7, 1(2014), pp. 71-75.
[16] Li, F.; Yu, J. J.; Jiang, X. H.; Du, Q. S.; Song, H. L. Study on the buried ancient river system in the south Yellow Sea. // Oceanologia Et Limnologia Sinica. 22, 6(1991), pp. 501-508.
[17] Gu, Z. F.; Zhang, Z. X. Shallow seismic stratigraphy and sedimentary character in the western South Yellow Sea. // Marine Geology and Quaternary Geology. 29, 4(2009), pp. 95-106.
[18] Liu, S. H.; Feng, A. P.; Li, P.; Du, J.; Hu, W. F. Preliminary analysis of the ancient channels buried shallower than 50 meters in the coastal and offshore areas of the Yellow River delta. // Coastal Engineering, 32, 4(2013), pp. 22-30.
[19] Yang, Z. G.; Wang, S. J.; Zhang, G. W.; Li, S. Q.; Liu, J. Evolution model for South Yellow Sea tidal sand ridges during trans-gressions in deglaciation. // Marine Geology & Quaternary Geology. 21, 3(2001), pp. 1-10.
[20] Song, Z. J.; Zhang, Z. X.; Huang, H. J. Characteristics and depositional setting of the high resolution shallow seismic profile in the South Yellow Sea. // Marine Geology and Quaternary Geology. 25, 1(2005), pp. 33-40.
[21] Liu, J.; Saito, Y.; Kong, X. H.; Wang, H.; Wen, C.; Yang, Z. G.; Nakashima, R. Delta development and channel incision during marine isotope stages 3 and 2 in the western South Yellow Sea. // Marine Geology. 278, 1-4(2010), pp. 54-76. DOI: 10.3724/SP.J.1140.2009.06001
[22] Liu, J.; Saito, Y.; Wang, H.; Zhou, L. Y.; Yang, Z. G. Stratigraphic development during the late Pleistocene and Holocene offshore of the Yellow River delta, Bohai Sea. // Journal of Asian Earth Sciences. 36, 4-5(2009), pp. 318-331.
[23] Ren, M. D; Wang, N. L. // Introduction to the modern sedimentary environment. / Science Press, Beijing, 1981, pp. 32-46.
[24] Lan, X. H.; Zhang, X. J.; Zhao, G. T.; Zhang, Z. X. Distributions of rare earth elements in sediments from Core NT1 of the South Yellow Sea and their provenance discrimination. // Geochimica. 38, 2(2009), pp. 123-132.
[25] Lan, X. H.; Zhang, Z. X.; Li, R. H.; Ding, D. Provenance study of sediments in Core NT2 of the South Yellow Sea. // Acta Sedimentologica Sinica. 28, 6(2010), pp. 1182-1189.
[26] Song, Z. J.; Gong, L. M.; Gao, L.; Gu, Z. K.; Yu, J. F.; Tang, W. J. Study on paleochannel distribution in the western South Yellow Sea during early Wurm Glaciation based on ArcGIS. // International Journal of Earth Sciences and Engineering. 7, 4(2014), pp. 1506-1510.
[27] Liu, K.; Zhuang, Z. Y.; Liu, D. Y.; Ye, Y. C. Pattern discrimination and characteristic analysis of the buried ancient channels in the inner continental shelf out of Yangtze River. // Transactions of Oceanology and Limnology. 1(2009), pp. 79-87.

Authors' addresses

Zhaojun Song, Ph.D. Assoc. Prof. *(Corresponding author)*
Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Minerals, College of Earth Science & Engineering, Shandong University of Science and Technology, Room 254, 579 Qian Wan Gang Road Economic & Technical Development Zone, Qingdao, 266590, Shandong Province, P. R. China
E-mail: songzhaojun76@163.com

Jianping Li, Master
Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Minerals, College of Earth Science & Engineering, Shandong University of Science and Technology, Room 254, 579 Qian Wan Gang Road Economic & Technical Development Zone, Qingdao, 266590, Shandong Province, P. R. China
E-mail: 1378236354@qq.com

Zhenkui Gu, Ph.D.Candidate
Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A, Da Tun Road, Chaoyang District, Beijing, 100101, P. R. China
E-mail: 614175345@qq.com

Wenjia Tang, Master
Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Minerals, College of Earth Science & Engineering, Shandong University of Science and Technology, Room 254, 579 Qian Wan Gang Road Economic & Technical Development Zone, Qingdao, 266590, Shandong Province, P. R. China
E-mail: 1468915028@qq.com

Jifeng Yu, Ph.D. Professor
Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Minerals, College of Earth Science & Engineering, Shandong University of Science and Technology, Room 424, 579 Qian Wan Gang Road Economic & Technical Development Zone, Qingdao, 266590, Shandong Province, P. R. China
E-mail: yujifeng05@163.com

Luo Gao, Master
Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Minerals, College of Earth Science & Engineering, Shandong University of Science and Technology, Room 254, 579 Qian Wan Gang Road Economic & Technical Development Zone, Qingdao, 266590, Shandong Province, P. R. China
E-mail: 291539916@qq.com