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Preliminary evidence for 17 coastal terraces on Fildes Peninsula, King George Island, Antarctica

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Abstract This study confirms the presence of 17 coastal terraces on Fildes Peninsula, Antarctica based on field observations and grain size analysis. The terraces formed by isostatic uplift during climate warming and glacier melting, and each level corresponds to a relatively stable period of climate. The grain size characteristics indicate an overlapping sedimentary origin for the sediments on the coastal terraces. The consistency of regional sea level rise, climate change, and glacial area suggest the presence of similar coastal terraces on King George Island since 18.0 ka.

Keywords **Fildes Peninsula, coastal terrace, grain size characteristics**

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1 Introduction

Coastal terraces have been described and studied comparatively in Antarctica, and linked with isostatic uplift and sea level change[1-6]. Mashacher[7] discovered marine plants, shells, and animal bone at 18 m and 24 m ASL in Zhenzhu Stream Valley on Fildes Peninsula. Li and Zhang[8] and Li et al.[9] confirmed the presence of neritic deposits in the valleys of Xisi River on the peninsula based on paleontology and grain size analysis. Yang and Chen[10] analyzed diatom fossils from Yanou Lake on Fildes Peninsula, and confirmed it as a neritic environment during the Quaternary. In their work, Xie and Cui[11] discussed the environmental implications of the platform on King George Island and five coastal terraces have been discovered on Fildes Peninsula[12-14]. In this paper, based on field observations and grain size analysis of the sediment, we report 17 coastal terraces on Fildes Peninsula.

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2 Study area and methods

2.1 Fildes Peninsula

Fildes Peninsula (62°08′48″–62°14′02″S, 58°53′40″–59°01′50″W) is 10 km long, 2.5–4 km wide, and covers an area of 30 km^2. It is the largest ice-free area with approximately 20 ka years of history on King George Island (Figure 1)[8]. The highest mountain is Horatio Stump at 164.3 m ASL. The tertiary volcanic rocks on the peninsula are mainly high-Al basalt and basaltic andesite, as well as andesite and dacite[15]. The basaltic-andesitic lavas that make up most of the peninsula, the thin-layered pyroclastic-sedimentary fossil-bearing strata, subvolcanic intrusions, and dykes from different effusive periods show that tertiary volcanic activity has continued to the present on the Antarctic Peninsula[16-17].

Fildes Peninsula has two major landforms: mountains mainly consisting of bedrock over 50 m ASL, and rising coastal terraces. Both landforms have been eroded by glaciers. The five coastal terraces mainly contain loose

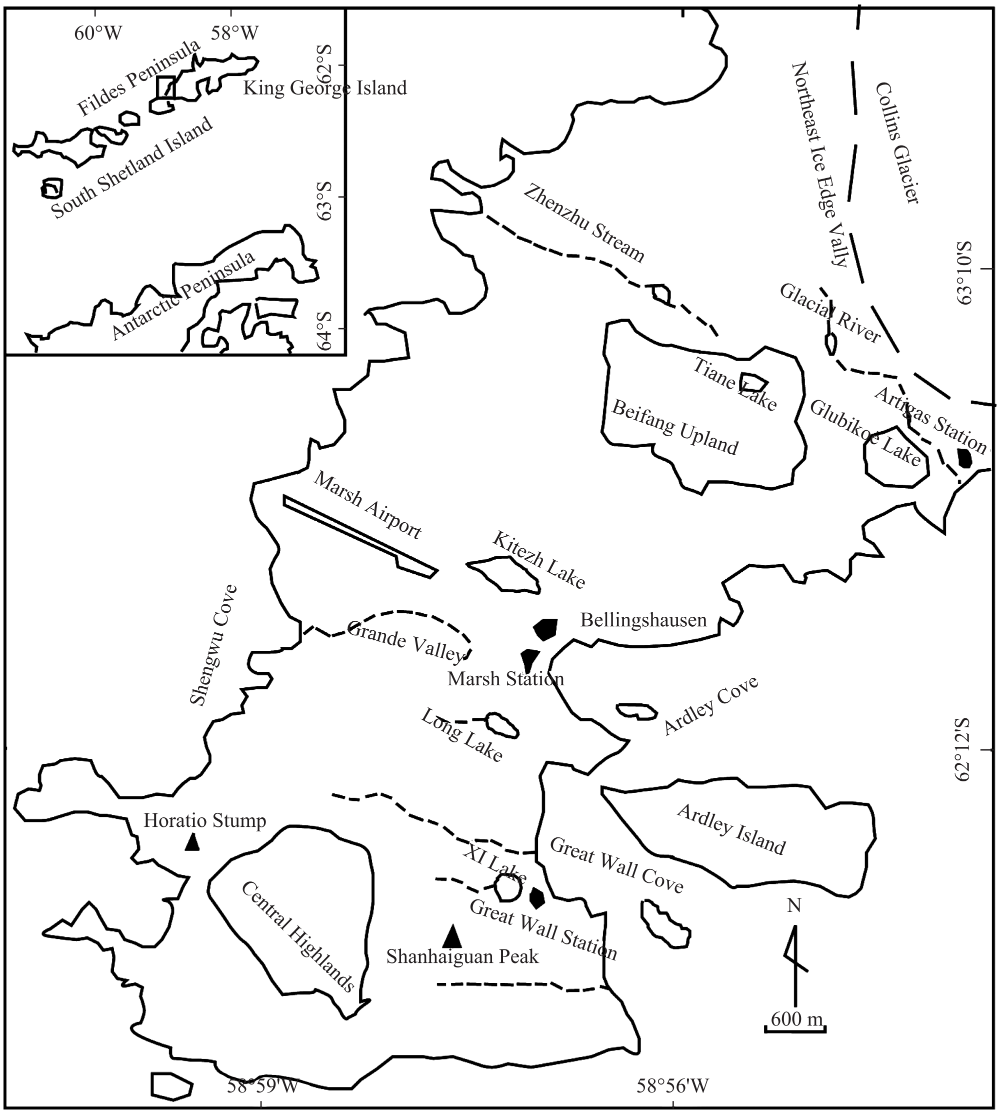

Figure 1 Location of Fildes Peninsula, Antarctica.

gravel sand deposits on the east coast, and the fifth level is a highly developed abrasion terrace at 40–50 m ASL[5,12-13]. The weathering rate on the peninsula ranges from 0.012 to 2.041 $mm \cdot a^{-1}$, with an average rate of approximately 0.200 $mm \cdot a^{-1}$. The planar denudation rate ranges from 28.94 to 4 940.45 $g \cdot m^{-2} \cdot a^{-1}$, with an average rate of approximately 552.13 $g \cdot m^{-2} \cdot a^{-1}$[8]. A prolonged lack of much surface runoff has greatly lowered the migration rates of terrestrial material and shortened the transmission distance, resulting in deposition near the origins. Strong physical and relatively weak biochemical processes have led to the formation of a thin pedosphere, including frozen entisol, humid frozen cambisol, normal frozen cambisol, and frozen organic soil.

2.2 Materials and methods

We described the landforms, measured elevation using GPS from Great Wall Bay to Shanhaiguan Peak and Horatio Stump, and collected approximately 1.0 kg of unconsolidated sediment using a bamboo spoon at 2–3 cm depth below the surface on the 15th Chinese National Antarctic Research Expedition during 1998–1999. We also collected a 67.5 cm-long lake sediment core from the 3rd coastal terrace, and 11 samples (HS1–HS11) from a sea cove on the 5th terrace.

2.3 Grain size analysis

The sieve analysis method was used to analyze the grain size of sedimentary samples from the coastal terraces. The sediments are characterized by the presence of a sieve aperture and a graded interval of approximately 0.5 φ. The sea beach on the peninsula contains abundant gravel, and the sediments mainly consist of single gravel, sands, and silts. Gravel of approximately 1–2 cm can be transported by waves and high winds[8]. Previous studies have determined the median size (*Mz*) of coastal depositions in Antarctica as −2.8 φ (6.96 mm) and the grain size of sediments in the Larsemann Hills ranges from 0.40 to 10.0 mm (−3.32–4.64 φ)[18].

The storm ridges on the peninsula are composed of gravel approximately 2–3 cm in diameter, located on the gravel beach of the abrasion terraces at 40–50 m ASL, and usually above the coastal terrace surface at approximately 1.0 m[12-13,19-20]. The weight of grain sizes greater than 1 mm on the terraces accounted for approximately half of the total weight. Grain sizes ranging from 0.040 mm to 16.0 mm (−4–4.64 φ) was used to characterize the samples.

3 Morphologic characteristics of coastal terraces

We confirmed the presence of 17 coastal terraces on the peninsula during the 15th Chinese National Antarctic Research Expedition that took place during 1998–1999. The morphologic characteristics of the coastal terraces at all levels are summarized in Table 1 and shown in Figures 2a and 2b.

The coastal sediments are divided into two formations: arenous and pebbly sediment. The former mainly contains sand and silt, and the latter is made up of gravel of approximately 3–5 cm and 15–20 cm. Arenous and pebbly beaches co-exist on the peninsula.

The samples collected from the coastal terraces are sub-Antarctic brown earth. Field sampling records confirmed the presence of pebbles and sand with marine characteristics on all terraces. The widespread presence of pebbles indicates the uplift of coastal terraces. The ancient sea caves and cliff, and the typical coastal landforms observed on the 1st, 5th, 7th, 8th, 11th, and 12th terraces, provide further evidence that the platforms below the 12th level are coastal terraces. The difference in elevation between adjacent terraces ranged from 3.05 to 31.2 m, and the largest water level difference in tides was 2.5 m, recorded at the Uruguay Station, King George Island, Antarctica between 1999–2000. The sea level has been uplifting since 20 ka BP and the water level difference of the tides is less than the present difference based on tidal dynamics[21]. Terraces that formed during different periods have different elevations. The maximum width of the 17 terraces was 120 m, and the minimum was 6 m, which reflects the different times the terraces have remained stable during the uplifting process. All terrace widths were measured from the terraces between Great Wall Bay and Horatio Stump. The widths of different platforms are not comparable because they are connected along the direction of the waves, the rigid shoreline, and landforms[22-24].

The loose sediments on the ice-free regions of the Fildes Peninsula consist of weathered detritus and old glacial tills that have continued to refine, sort, and migrate, and even weather chemically during glaciations[25]. Coastal pebbles underwent primary physical weathering, and became a broken gravel plexus (Figure 3). The pebbles on the coastal terraces have a smooth surface, weak weathering traces, and some lichen growing on the surface of the higher terraces. In summary, weathering has little impact on the plasma of the sediments.

Horatio Stump has been ice-free since 18.0 ka BP and its lifting can be attributed to the ice volume change of the

Table 1 Platform and physical characteristics of sediments of coastal terraces of 17 levels in Fildes Peninsula

Project Level	Elevation/m	Width/m	Cobble	Groove	Vegetation	Freeze-thaw earths	Rounding	Sorting	Glacial boulder
1	4	10	*****	+	Moss	-	III	I	-
2	7.05	10	****	-	Moss	-	III	II	-
3	11.93	120	****	+	Moss	+	III	III	+
4	18	10	***	?	Moss	?	II	II	-
5	28.46	10	*	+	Moss, lichen	+	II	II	-
6	41.57	120	**	-	Moss	+	II	III	-
7	47.12	40	***	+	Moss	-	IV	II	-
8	59.35	20	*	-	Lichen	-	II	II	-
9	71.61	12	*	-	-	+	I	I	-
10	100.81	10	*	-	Moss	+	II	II	-
11A	104.11	50	**	+	Moss, lichen	+	II	II	-
12	120.8	40	***	+	Lichen	+	II	II	+
13	131.46	7	**	-	Lichen	+	II	I	+
14	135.39	6	*	-	Lichen	+	II	II	-
15A	147.02	8	*	-	Lichen	+	I	II	-
16	154.92	20	*	-	-	+	II	II	-
17	163.78	55	●	-	-	+	IV	IV	-

Note: 1, Mosses indicate humid, lichens indicate dry environment, fruticose lichens indicate coarse gravel environment. 2, –: no, +: have; *the quantity of gravel; ● sand; I: bad, II: general, III: good and IV: better. 3, Research result about coastal terraces of 4th level is from Xie[16].

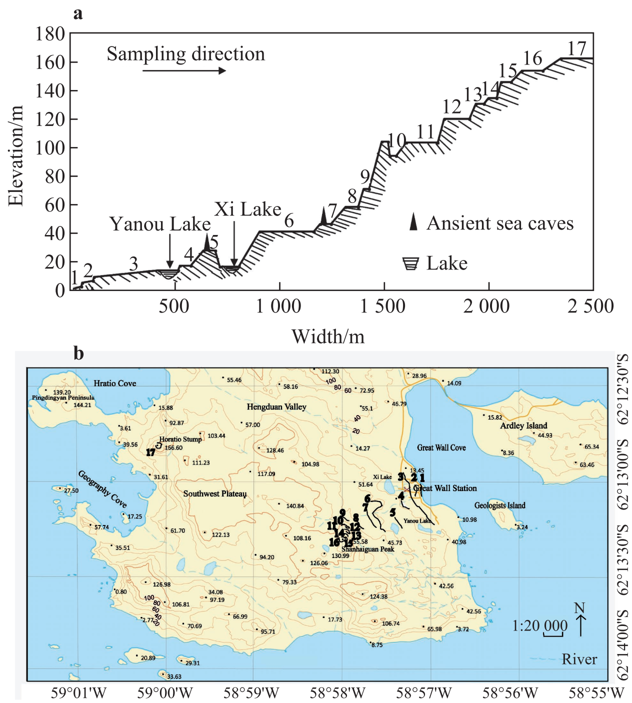

Figure 2 Coastal terraces of 17 levels.

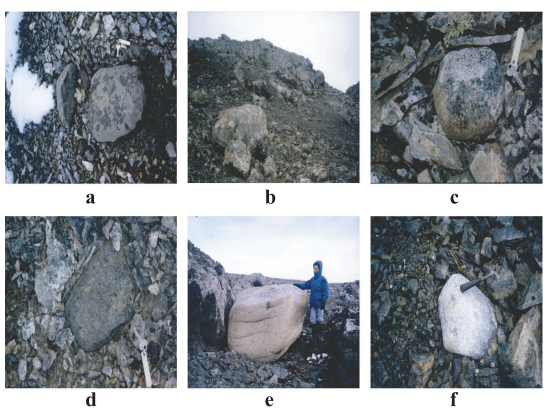

Figure 3 Platform and cobble of ancient beach in Fildes Peninsula. **a**, **b**, **c**, and **d** respectively shows the condition in coastal terraces of 5th, 9th, 11th, 13th levels, and **e** and **f** shows the granitic erratic boulders in coastal terrace of 10th and 11th levels.

Collins and Nelson ice caps. The surface of Horatio Stump has a large amount of fine sands (Mz=398 μm) dating to 18.0 ka (thermoluminescence dating)[7]. We inferred that Horatio Stump has uplifted from the past beach to the present terrace since 18.0 ka BP because of a warming of the climate and ice-retreat. Relatively stable periods of climate indicate the stability of the earth's crust, and the 17 coastal terraces were formed under erosion of waves during these periods. The different widths of the terrace platforms reflect stable climate periods of different lengths since 18.0 ka.

Matching 17 coastal terraces should also occur on the King George Island since 18.0 ka BP because of the similar regional sea level and climate change, and glacial coverage. A previous study reported wide coastal terraces at 5 m ASL, 50 m ASL, and 200 m ASL on Seymour Island, on the Antarctic Peninsula[26]. Three coastal terraces, located at high (21–24 m, 32–35 m), mid (10–17 m), and low (3–5 m) levels were found at Santa Marta, Groft Bay, James Ross Island[27]. Holocene terraces were also found on Trinity Peninsula, in West Antarctica[28]. Terraces of different elevations have also been recorded on the Larsen Bay coast, on Seymour Island, Antarctic Peninsula. The terrace at 3 m was formed between 2 ka BP and 2.1 ka BP, and the terrace at 0.5–1 m was formed at 1.2 ka BP[29]. However, the actual chronology of the terrace at 0.5–1 m is 0 because the water level difference of the tides is 2.5 m.

4 Results and discussion

4.1 Probability cumulative grain size curves

As shown by the probability cumulative grain size curves for the sediments on the 17 coastal terraces, the curve of the 2nd terrace is characteristic of double-section control (Figure 4). The rolling particles account for 95%, and belong to a typical gravelly beach. The curves for the 5th and 9th terraces are of three-section control (Figure 4). These terraces contain rolling, saltation, and suspension particles, suggesting that previous beach deposition was mixed with aeolian deposits, and the saltation and suspension particles therefore increased. The curves for the 7th, 10th, and 17th terraces were four-part form (Figure 4). The terraces contain double saltation particles, indicating a shallow sea depositional environment and an intertidal zone that is easily eroded by high energy waves. The curves for the other terraces reflect the original sedimentary environment and late erosion.

The sediments on all terraces contain coarse particles, and the grain-size parameters show obvious differences: Mz ranges from 234 μm to 5 169 μm, C from 8 111 to 77 708 μm, the coarse section from −2.51 to 0.60 φ, the fine section from 1.61 to 4.17 φ, skewness from −0.427 5 to 0.488 0, and stridency from 0.58 to 2.23. The sorting of the sediments is poor, suggesting a complex sedimentary environment.

4.2 Discriminant function analysis–identification of the sedimentary environment

Rocks are usually present only during the physical weathering stage in temporary ice-free areas in Antarctica, and brown earth is poorly developed in sub-Antarctica. As a result, the grain size of sediments is coarse and the sorting is poor. Discriminant function analysis, as proposed by Sahu[30], is inconsistent with the actual environment, and the functions need statistical calculations. We used three beach sediment samples from Larsemann Hills, East Antarctica, and three samples from the 1st, 2nd, and 3rd level coastal terraces on Fildes Peninsula, West Antarctica[19] as examples of standard beach deposition. We also selected three aeolian deposits from Larsemann Hills, and four aeolian lake samples from

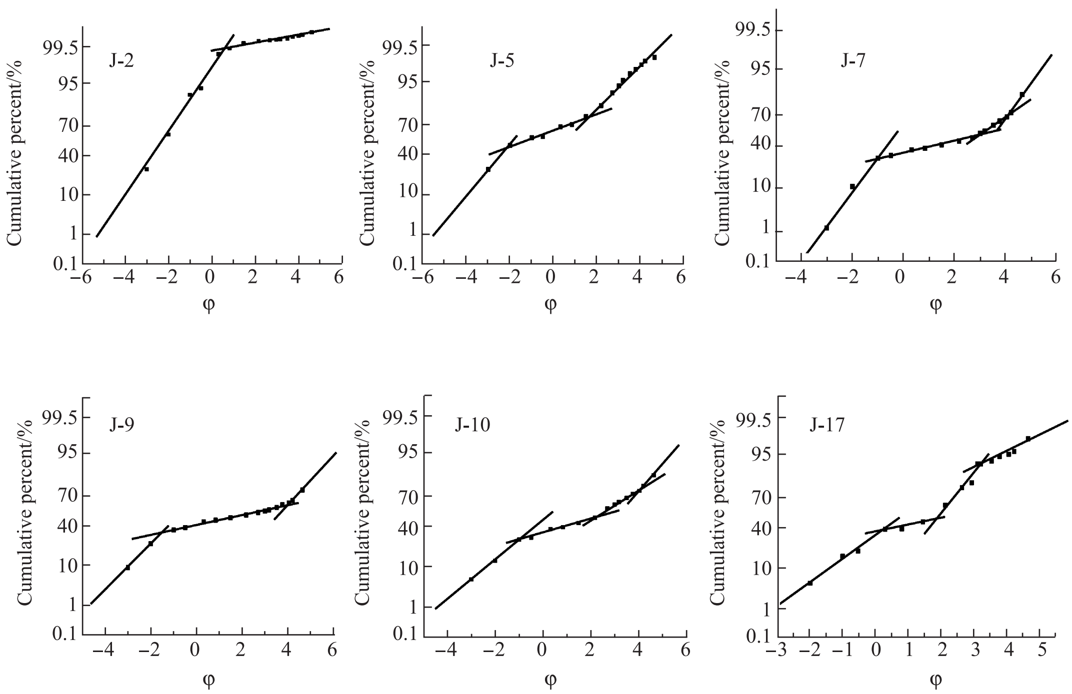

Figure 4 Probability cumulative grain size curves for sediments in coastal terraces of 2nd, 5th, 7th, 9th, 10th, 17th level.

Tuanjie Lake[8] to represent standard aeolian deposits. The 14 samples were analyzed using Statistic Package for Social Science. The discriminant function is calculated as follows: $Y_{aeolian:beach} = 1.704Mz - 0.877\sigma^2_1 + 4.432SK_I - 2.318Kg + 5.160$, where Mz is the median particle diameter of deposits, is σ_1 is= standard deviation, SK_I is skewness and Kg is kurtosis.

This function is better suited to identifying aspects of the sedimentary environment, and the origin of sediments in Antarctica. We also applied it to 16 coastal terraces (Tables 2 and 3), and its application to the 4th terrace has been verified by Xie[12].

Table 2 Grain size parameters of sediments in coastal terraces of 17 levels

	Sections of curve	Coarse section/φ	Fine section/φ	σ_1	SK_I	Kg	Mz/μm	C/μm
J-1	3	0.19	1.93	2.110	0.082 9	1.22	3 442	77 708
J-2	2	0.60		1.195	0.000 0	1.02	5 169	36 002
J-3	3	−0.86	2.87	3.085	0.042 9	0.71	447	23 103
J-5	3	−2.15	1.61	2.584	0.274 4	0.70	1 798	41 070
J-6	3	−0.85	2.24	2.785	−0.116 9	0.77	409	20 112
J-7	4	−1.03	4.12	2.705	−0.427 5	0.58	234	8 112
J-8	3	−0.50	3.95	2.443	0.350 5	2.23	1 133	15 032
J-9	3	−1.55	4.04	3.361	−0.177 2	0.61	328	24 590
J-10	4	−1.01	4.15	2.850	−0.289 6	0.68	291	20 112
J11-A	4	−0.97	3.86	2.697	0.032 7	1.69	458	14 123
J11-B	3	−1.18	4.09	2.863	0.135 1	0.81	616	26 538
J-12	3	−1.10	1.45	2.933	−0.132 0	0.79	502	30 274
J-13	3	−1.07	2.59	2.867	0.488 0	0.68	1 077	25 281
J14	3	−0.84	2.44	3.008	0.360 0	0.76	1 154	46 851
J15-A	4	−1.51	4.17	2.884	−0.395 7	0.67	295	19 160
J15-B	5	−1.58	4.14	3.043	−0.343 3	0.69	302	18 636
J-16	3	−1.64	1.69	3.073	−0.171 4	0.82	302	14 520
J-17	4	0.21	3.14	1.820	−0.403 5	0.85	398	8 259

Table 3 Discriminant functions analysis of coastal terraces

Sample ID	F-1	F-2	F-3	S-1	S-2	S-3	ZH-01	ZH-3	ZH-07	ZH-10	ZH-14	ZH-19				
Type	1	1	1	2	2	2	1	1	1	1	1	1				
Sample ID	J-1	J-2	J-3	J-5	J-6	J-7	J-8	J-9	J-10	J-11	J-12	J-13	J-14	J-15	J-16	J-17
type	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1

Note: 1: Aeolian deposit or Aeolian lake sediment. 2: Beach depositions. ZH-01~ZH-19: Aeolian lake sediment; S-1~S-3: beach; F-1~F-3: Aeolian deposit; J-1 and J-2 are coarse gravel beach according to field observation

Based on the discriminant function analysis, Tuanjie Lake is an aeolian lake. The sediments from the 15 terraces are beach depositions, which show that the platform has 17 coastal terraces, and only J-17 is an aeolian deposit. J-17 is located on the top of Horatio Stump and its sediments may be aeolian. Horatio Stump is the highest peak on Fildes Peninsula, and the provenance of the beach deposition is not apparent. The sediment on J-17 is not beach sediment, and may instead be a mixture of weathering products, aeolian or neritic deposits.

4.3 *C-M* diagram

The *C-M* diagram is formed by sample points from a deposit defined by *C* (the one-percentile) and *M* (the median of the grain-size distribution), and is plotted at logarithmic scales. Specific wind conditions, freeze-thaw action, and geological events may make the *C-M* diagram difficult to interpret for Antarctica[30]. Currently, there are no typical *C-M* diagrams of sedimentary samples in Antarctica.

In this study, we used 200 published data points from different sedimentary patterns from Antarctica to draw the *C-M* diagram. The diagram shows a clear ‘S’ region, similar to a typical *C-M* diagram. However, the *C* and *M* values have an extended range: the maximum *C* value is 100 000 μm and the maximum *M* value is 10 000 μm, and the minimum *C* value is 100 μm and the minimum *M* value is 7 μm (Figure 5). The graph partition is similar with the typical *C-M* diagrams, and it can be subdivided by points N, O, P, Q, R, S into five segments NO, OP, PQ, QR, RS each of which corresponds to a particular sedimentation mechanism[31] (Figure 5):

(1) Segment NO: The shingle deposits most likely formed from rolled grains and have better sorting, similar to beach sediments.

(2) Segment OP: The sediments are a mixture with a variable proportion of rolled grains and suspension sediments. The *C* values display insignificant changes and are greater than 20 000 μm in diameter. The *M* values diminish gradually.

(3) Segment PQ: The depositions are mainly formed from suspension sediments, and contain little rolled grains. The *C* values show a clear change, whereas the *M* values have little variability, and the diagram is nearly vertical to the *M*-axis.

(4) Segment QR: Graded suspension where the sediments carried by exogenetic forces are fine. The particle sizes and density stratification of the sediments are not uniform. The *C* values are proportional to those of *M*, and the sorting of fine and coarse sediments is similar.

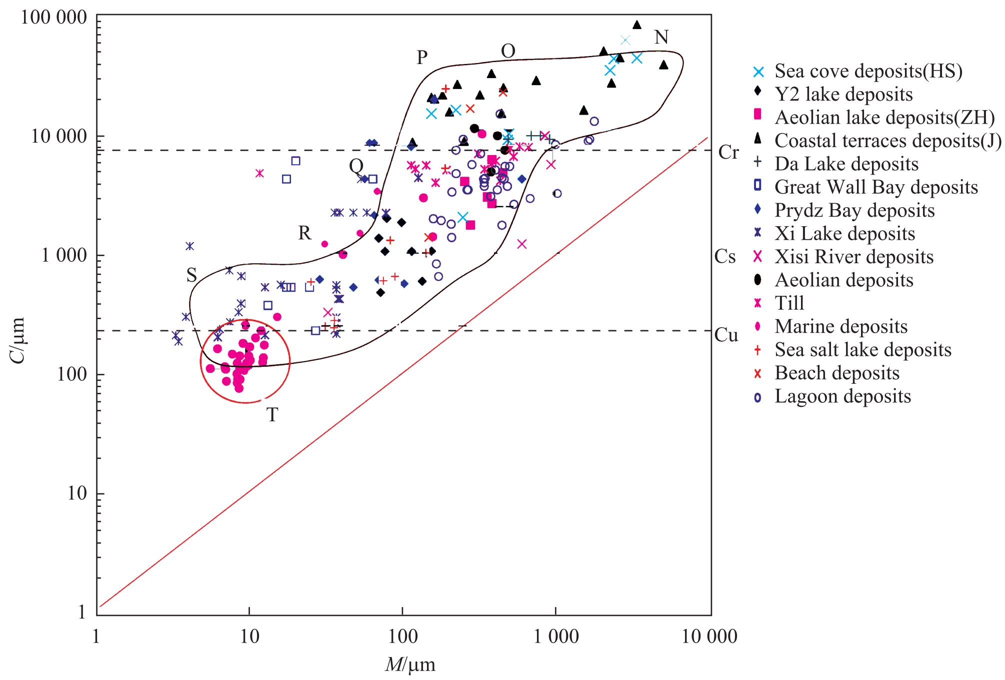

Figure 5 Grain size data of Sea cove (HS), Y_2 lake, Aeolian lake (ZH), coastal terraces deposits are from our study; grain size data of Xi Lake deposits are from Xie and Li[32]; Prydz Bay, till, marine, sea salt lake, beach and lagoon deposits are from Xie[33]; Da Lake and aeilian deposits are from Li[34], Xisi River and Great Wall Bay are from Li[35].

(5) segment RS: Uniform suspension where the grain size of the sediments is finer. The sediments are a mixt ure of silt and clay, and the coarsest particles are thick silt. The *M* values decrease gradually, and the *C* values remain unchanged. The segment in the diagram is approximately parallel to the *M*-axis, the maximum *C* value is approximately 700 μm, and the *M* value is usually less than 100 μm.

The *C*-*M* pattern is subdivided by points N, O, P, Q, R, and S into five segments, each of which correspond to a particular sedimentation mechanism, which is expected from a *C*-*M* diagram in Antarctica.

C_u: The *C* value near point R in segment RS represents the size of the coarsest particle in uniform suspension and C_u is 220 μm.

C_s: The *C* value near point Q in segment QR represents the size of the coarsest particle in graded suspension and C_s is 1 000 μm. C_s usually ranges from 500 to 1 000 μm.

C_r: The *C* value near point P in segment PQ represents the particle size of easily rolling transport and C_r is 7 900 μm.

The above three values define the critical particle size of the different types of transport on King George Island. A gap exists between the C_s- and C_r-values in natural sediments and the particles between them move through saltation transport.

The *C* and *M* values of ancient cave sediment samples on the 5th level coastal terraces plot in the rolling transport segment. The values of terrace deposits also occur mostly in the rolling transport segment. Only the values for J-7 and J-17 are in the rolling and suspension transport segment, which confirms that the sample site on the 17th terrace is reworked by wind. The values of the Y2 lake sediments on the 3rd level terraces plot mostly in the graded suspension segment, overlapping with a sea salt lake, and the partial values are in the uniform suspension segment and overlap with a shallow sea, such as the Great Wall Bay. In summary, these results further verify the platform as 17 coastal terraces.

5 Conclusions

(1) The Fildes Peninsula on King George Island has 17 coastal terraces.

(2) The grain size of deposition on the 17 terraces follows a Gaussian distribution; *Mz* ranges from 234 μm to 5 169 μm; *C* from 8 111 to 77 708 μm; the coarse section from −2.51 to 0.60 φ; the fine section from 1.61 to 4.17 φ; skewness from −0.427 5 to 0.488 0; and stridency from 0.58 to 2.23. The sorting of sediments is poor, indicating a complex sedimentary environment.

(3) Samples collected from the 7th and 17th coastal terraces contain aeolian deposits. The standard *C*-*M* diagram for Antarctica defines the critical particle sizes of different transport combinations and distinguishes the origin of sediments.

(4) Horatio Stump has uplifted from an ancient beach or shallow sea to the present-day 17th coastal terrace because of climate warming and ice-retreat since 18.0 ka. Relatively stable periods of climate indicate the stability of the earth's crust, and the 17 coastal terraces formed under the erosion of waves during these periods. The different widths of the terrace platforms reflect stable climate periods of different length since 18.0 ka.

(5) The consistency of regional sea level eustacy, climate change, and glacial area suggest the occurrence of similar coastal terraces on King George Island since 18.0 ka.

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