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Distributions of surface sediments surrounding the Antarctic Peninsula and its environmental significance

WANG Chunjuan[1,2], CHEN Zhihua[2*], LI Chunshun[2], DU Dewen[2], YAN Shijuan[2] & ZHU Zhiwei[2]

[1] China University of Geosciences (Beijing), Beijing 100083, China;
[2] The First Institute of Oceanography, SOA, Qingdao 266061, China

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Abstract We analyzed grain size composition to provide information on the types and distributions as well as depositional varieties of marine surface sediments from the area surrounding the Antarctic Peninsula. The samples retrieved from the study area contain gravel, sand, silt and clay. As suggested by bathymetry and morphology, the study area is characterized by neritic, hemipelagic and pelagic deposits. The glacial-marine sediments can be divided into two types, residual paratill and compound paratill, which are primarily transported by glaciers and as ice-rafted debris. Ocean current effects on deposition are more obvious, and the deposit types are distributed consistently with terrain variations.

Keywords **Antarctic Peninsula, surface sediments, grain size, environmental significance**

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1 Introduction

Grain size is one of the basic properties of sediments, and grain size analysis is a classic sedimentological method. We usually use the composition, parameters of particle size, and various kinds of diagrams to identify the type of sedimentary environment and to interpret the sediment transport processes[1]. Sediment granularity is an important characteristic for inferring the sedimentary dynamics and plays a large role in comprehensively understanding the results of sediment and depositional processes. It has long been used in the division of sediment types to determine ways of material migration and the sedimentary dynamic environment. Granularity can help distinguish between sedimentary environments and also has important reference significance[1].

Important sedimentary characteristics in the area surrounding the Antarctic continent are strongly affected by glaciations[2]. Glaciations directly shaped the sedimentary features of Antarctica's marginal seas and also constantly reformed the sea floor features through the effect of currents[3]. The surface sediments in the marine realm around the Antarctic Peninsula are more profoundly affected by glaciation. This study analyzed data provided by the 1st and the 28th Chinese National Antarctic Research Expeditions, and used other publicly available data. We investigated grain size distribution and composition to discuss the sediment sources and their characteristics.

2 Geological setting

The study area encompasses the western, eastern and northern sides marine areas surrounding the Antarctic Peninsula. It is a unique regional area, located between the Antarctic continent and the South American continent in the transition zone between the South Atlantic Ocean and the Pacific Ocean. To the southwest is the Bellinsgauzen Sea, and southeast is the Weddell Sea. The Antarctic Peninsula is the largest and extends the greatest distance (to 63°S) into the Southern Ocean. This area of the Antarctic continent has a relatively warm climate, so it has also been the most sensitive

* Corresponding author (email：chenzia@fio.org.cn)

to climate and environmental changes in the Antarctic over the past century[4-6]. Furthermore, the rapid disintegration and collapse of its ice shelf has had a profound influence on the world's oceans and climate change[7-10].

The main terrestrial geomorphic units include: the Antarctic Peninsula, the South Shetland Islands, and the South Orkney Islands. The main marine and seafloor features include: Drake Passage, Scotia Sea, South Scotia Ridge, Weddell Sea, Powell Basin, Jane Basin, and Brendsfield Strait[11]. The Weddell Sea is the largest marginal sea in the world with water depths of 4 500–4 700 m and a deep trench (8 428 m)[11]. In the Weddell Sea, cold and dense shelf water sinks and becomes Antarctic Bottom Water, which is the main source of deep water in the world's oceans. Over half of the bottom cold waters of the world's oceans stem from the Antarctic, most of which is produced in the Weddell Sea[11]. The currents found in the study area mainly comprised the Antarctic Circumpolar Current (ACC), Weddell Sea Bottom Water (WSBW), Deep Weddell Sea Water (WSDW), the Weddell Gyre and the Antarctic Peninsula Continent–Island Shelf Water[12]. The study area is located in the mixing region between ice and ocean, so it has glacial-marine sedimentary characteristics. This is exhibited as mixed sediments with formation features representing the glacial and marine realms. Anderson classified these sediments according to the glacial-marine sediment characteristics[13-16].

3 Data collection

The surface sediment samples were recovered by the 28th Chinese National Antarctic Research Expedition from the continental shelf and slope of the Powell Basin off of the South Orkney Microcontinent. During the expedition, the ship (R/V *XUE LONG* icebreaker) successfully sampled 23 sites, four of which contained samples with only a small amount of gravel. In addition, we used grain size data from 32 surface sediment samples recovered during the 1st Chinese National Antarctic Research Expedition, as well as the published data from 65 surface sediment samples[17] (Table 1). These datasets cover a wide area (58°S–67°S, 39°W–70°W) and a broad water depth range (45–5 356 m), which encompasses the surface water to deep water (Figure 1).

Table 1 Details of the surface sediment site locations in the study area

Sites of the 28th Chinese National Antarctic Research Expedition				Sites of the collection data			
Site	Longitude	Latitude	Depth/m	Site	Longitude	Latitude	Depth/m
D1-3	61°15′29″W	58°09′42″N	2 712	PS06/224	61°27′12″W	57°22′42″N	1 112
D1-5	61°48′30″W	57°11′12″N	367	PS1138-8	62°16′24″W	57°38′42″N	1 985
D1-7	62°16′10″W	56°35′27″N	1 100	PS1167-5	63°57′36″W	44°04′06″N	4 515
D1-9	62°45′33″W	55°59′46″N	212	PS1170-4	63°31′06″W	44°31′12″N	3 803
D2-2	60°26′23″W	54°53′16″N	3 475	PS1173-6	62°58′00″W	45°00′30″N	3 577
D2-3	60°49′03″W	54°35′23″N	1 310	PS1175-1	62°31′30″W	45°34′36″N	3 107
D2-4A	61°12′17″W	54°54′53″N	45	PS1179-1	61°35′42″W	48°07′06″N	3 125
D2-6	61°48′06″W	53°40′38″N	627	PS1184-6	62°16′18″W	57°22′30″N	1 882
D3-3	61°09′57″W	50°45′19″N	894	PS1186-3	62°20′48″W	57°56′24″N	1 976
D3-5	62°13′56″W	50°20′42″N	3 397	PS1327-1	62°16′30″W	57°38′48″N	1 979
D3-7	62°52′33″W	50°10′42″N	3 429	PS1333-1	63°13′60″W	61°38′60″N	890
D4-2	60°20′31″W	47°12′35″N	2 268	PS1333-2	63°14′06″W	61°39′09″N	878
D4-3	60°36′03″W	47°10′55″N	438	PS1338-1	62°53′49″W	60°04′00″N	1 085
D4-7	61°47′30″W	47°09′26″N	1 281	PS1340-1	62°15′43″W	57°29′13″N	1 979
D4-9	62°24′30″W	47°06′31″N	3 401	PS1341-1	62°15′20″W	57°28′18″N	1 979
D5-1	60°20′17″W	44°40′32″N	2 912	PS1342-1	62°14′42″W	57°29′42″N	1 980
D5-2	60°33′36″W	44°41′48″N	323	PS1343-1	62°13′25″W	57°30′13″N	1 980
D5-3	60°55′41″W	44°42′32″N	243	PS1346-1	62°17′12″W	57°27′30″N	1 971
D5-4	61°12′37″W	44°41′14″N	316	PS1347-1	62°13′24″W	57°27′15″N	1 962
D5-5	61°29′32″W	44°38′44″N	377	PS1357-2	62°13′54″W	57°25′60″N	1 948
D5-6	61°47′53″W	44°40′43″N	385	PS1509-2	65°00′00″W	42°00′48″N	4 671
D5-7	62°05′31″W	44°41′14″N	480	PS1537-2	61°59′20″W	55°52′59″N	2 036
D5-9	62°42′34″W	44°39′58″N	2 036	PS1538-1	63°23′20″W	56°59′56″N	267

(To be continued)

(Continued)

Sites of the 1st Chinese National Antarctic Research Expedition				Sites of the collection data			
Site	Longitude	Latitude	Depth/m	Site	Longitude	Latitude	Depth/m
J	62°07′30″W	57°57′00″W	400	PS1539-1	62°40′16″W	57°15′22″N	455
L1	62°50′36″W	60°20′30″N	860	PS1540-1	61°44′24″W	57°53′46″N	196
L2	62°46′00″W	60°26′30″N	120	PS1542-1	61°17′10″W	58°11′17″N	2 380
L3	62°43′48″W	60°41′30″N	116	PS1543-1	60°47′13″W	58°36′47″N	4 479
L4	62°50′12″W	60°45′36″N	194	PS1544-1	62°04′59″W	57°39′04″N	280
L5	62°51′36″W	61°06′00″N	302	PS1545-1	62°14′46″W	57°33′36″N	1 933
L6	62°44′54″W	61°02′36″N	128	PS1546-2	62°59′42″W	56°59′46″N	67
M1	62°12′12″W	58°55′00″N	100	PS1547-1	63°14′42″W	56°50′38″N	137
M2	62°11′42″W	58°48′30″N	230	PS1554-1	65°12′31″W	64°06′51″N	400
M3	62°14′24″W	58°51′42″N	345	PS1555-1	65°45′04″W	69°02′57″N	218
M4	62°15′48″W	58°45′58″N	510	PS1557-1	65°21′28″W	66°27′27″N	458
M5	62°15′30″W	58°42′06″N	370	PS1558-1	65°04′12″W	66°58′38″N	199
M6	62°19′24″W	58°43′24″N	461	PS1559-1	64°46′58″W	67°36′36″N	345
R1	62°13′54″W	58°17′24″N	525	PS1560-1	64°36′35″W	68°00′44″N	830
R2	62°10′48″W	58°19′60″N	520	PS1563-1	64°28′08″W	68°16′23″N	2 804
R4	62°06′48″W	58°23′30″N	400	PS1564-1	64°11′02″W	68°56′26″N	3 253
S2	62°33′06″W	56°28′36″N	278	PS1569-1	60°20′20″W	58°55′23″N	3 574
S3	62°17′18″W	55°06′12″N	528	PS1572-1	63°47′49″W	42°34′01″N	4 521
S4	61°44′18″W	55°43′18″N	1 098	PS1573-2	63°26′46″W	42°51′07″N	3 993
S5	61°11′06″W	56°23′18″N	578	PS1574-1	63°11′31″W	43°03′43″N	3 720
S6	61°29′24″W	57°43′00″N	462	PS1575-2	62°51′07″W	43°19′55″N	3 455
S8	62°24′30″W	61°40′24″N	180	PS1576-1	62°18′58″W	43°46′16″N	1 122
S9	63°30′00″W	62°31′00″N	180	PS1577-2	61°56′24″W	44°00′07″N	842
S10	62°48′12″W	63°11′06″N	1 700	PS1953-1	63°44′35″W	50°55′18″N	2 413
S11	62°12′00″W	63°51′42″N	4 198	PS1954-1	64°24′22″W	45°48′12″N	4 434
S19	64°33′06″W	68°53′42″N	3 128	PS1958-1	65°11′59″W	39°22′19″N	4 757
S20	65°30′12″W	68°00′00″N	335	PS2318-1	59°50′12″W	42°52′60″N	4 545
S21	66°49′18″W	69°19′42″N	278	PS2320-2	60°06′00″W	44°50′48″N	5 356
S23	62°22′36″W	58°07′30″N	654	PS2322-2	60°18′30″W	44°52′48″N	2 824
S24	63°22′30″W	60°34′18″N	478	PS2325-1	60°30′24″W	44°53′42″N	461
S25	63°07′12″W	60°03′30″N	992	PS2327-1	59°59′54″W	45°53′06″N	5 213
S26	64°24′30″W	61°40′60″N	378	PS2328-1	59°55′48″W	46°06′12″N	4 674
				PS2329-1	59°37′06″W	47°01′42″N	4 148
				PS2330-1	59°20′18″W	48°00′48″N	4 056
				PS2331-1	59°02′24″W	48°59′36″N	3 947
				PS2332-2	58°38′06″W	49°56′30″N	3 110
				PS2805-1	66°05′08″W	56°31′55″N	466
				PS2806-1	65°59′02″W	53°44′10″N	1 500
				PS2808-1	66°04′53″W	52°25′00″N	2 869
				PS2809-1	66°05′25″W	52°14′20″N	2 780
				PS2811-2	66°16′33″W	50°50′15″N	3 152
				PS2812-1	66°33′13″W	50°00′44″N	3 430

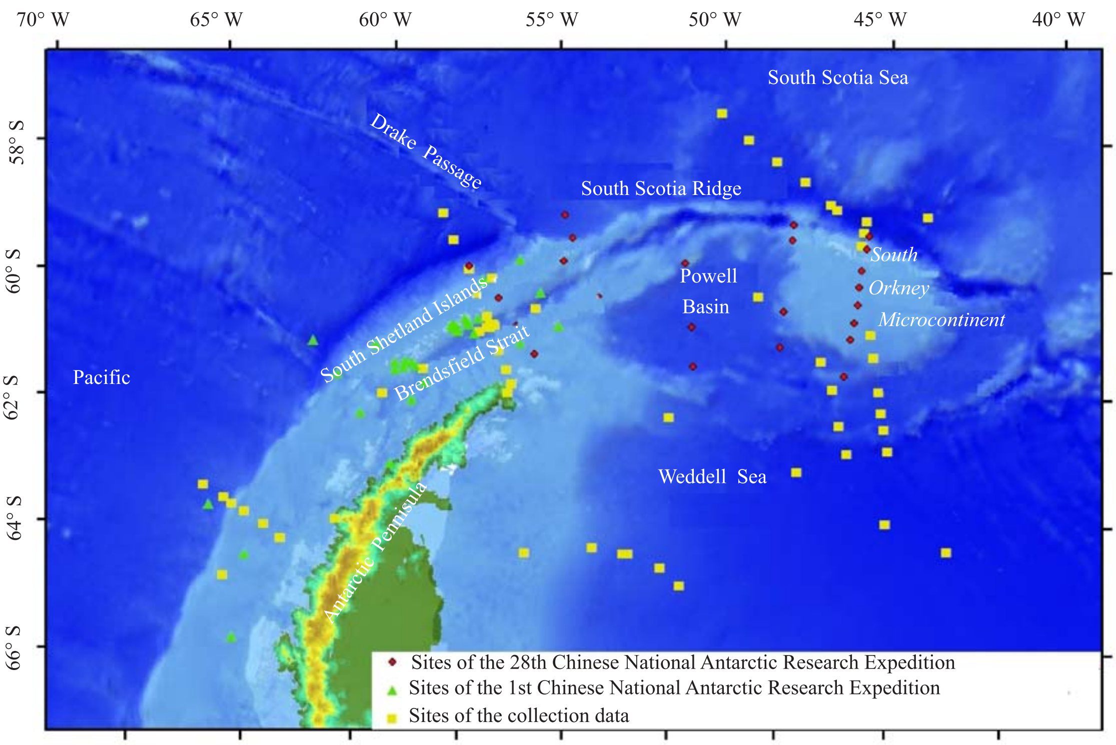

Figure 1 Map of the surface sediment locations in the area surrounding the Antarctic Peninsula.

4 Methods

The surface sediment samples recovered during the 28th Chinese National Antarctic Research Expedition were described on site while the grain size analyses were performed in the laboratory. Because of the particle size variability, the grain size analysis involved both sieve analysis and laser particle size analysis. The sieve analysis method is suitable for coarser particle sizes (>0.063 mm), which is also an appropriate method for moraine granularity analysis. By using quartation sampling, referencing the sample dosage from the sample quality estimation table[18], we disperses the sample through different aperture sieves from coarse to fine, and then weighs different graded accounts to determine a percentage of each.

Fine-grained samples (<0.063 mm) were analyzed with a Mastersizer 2000 laser particle size analyzer (Malvern) with a measuring range of 0.02–2 000 µm, resolution of 0.01Φ and relative error of repeated measurement <3%. The analytical procedure included the following steps: (1) Add 15 mL of 15% H_2O_2 solution and 2 mL of 1% $Na_4P_2O_7$ solution, mix them and leave it for 12 h; (2) Place the mixture into a water bath (85℃) and heat it continuously for 2 h; (3) Cool the solution and remove particulate organic material from the sediment; (4) Add 5 mL of 10% HCl solution to remove calcareous organisms and carbonate. In our study, diatoms were also removed in the following procedure: (1) Add 20 mL of 1 M sodium carbonate solution and heat it continuously in an 85℃ water bath for 4 h; (2) Cool the solution and centrifuge it three times before using the laser particle size analyzer. The Udden–Wentworth scale of equal ratio particle size (Φ) was used for all particle sizes, and the method of moments was used to calculate the average particle size (μ), sorting coefficient (δ), skewness (Sk) and kurtosis (Ku) of the sediments[18].

In light of the complicated hydrodynamics and topography of the studied marine area, as well as the specific and variable geomorphic units at each of the sites, the surface sediments were classified as neritic continental (or insular) shelf clastic sediments, bathyal continental (or insular) slope sediments and abyssal sediments according to water depth and geomorphic units[19]. The continental or insular shelf clastic sediments (<510 m water depth) were designated according to Folk et al.[20], which reflects well the hydrodynamic environment and sediment genesis in continental shelf neritic regions. First, sediment particle size fractions were rated using the Udden–Wentworth scale[21]. Then, the sediment types were designated on the basis of the individual sediment fraction ratios. Samples containing pebbles (>2 mm) were designated using the Folk triangular diagram for classifying pebbly sediments involving pebble, silt and mud (Figure 2a) where the silt and clay percentages are represented by the mud percentage[22]. Sediments containing no pebble-sized particles were designated using the more detailed pebble-free Folk equilateral triangular diagram involving sand, silt and clay (Figure 2b)[23].

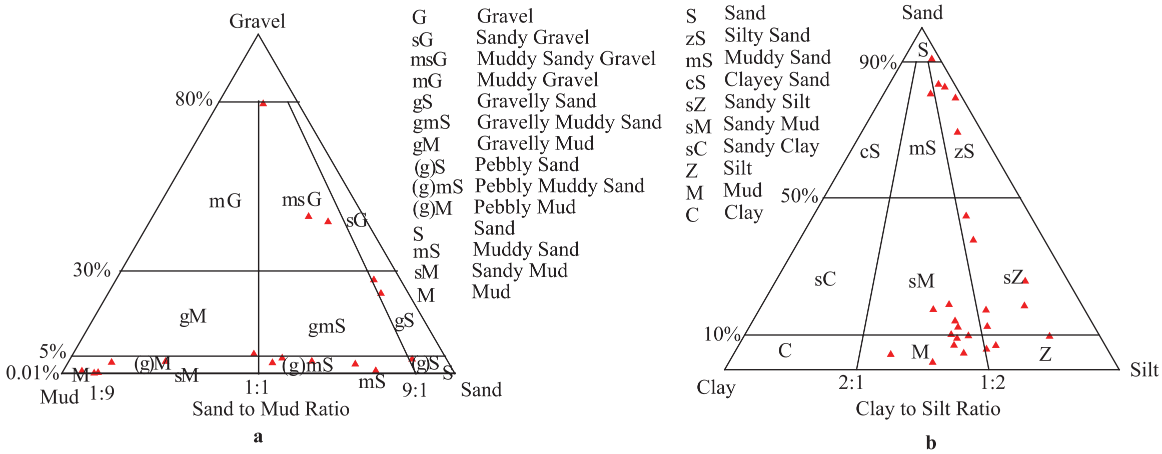

Figure 2 Folk's triangle diagram classification schemes of surface sediments used in the current study (**a**, pebble-sized particles; **b**, no pebble-sized particles).

5 Classification of the surface sediments

5.1 Classification and distribution of surface sediments

Surface sediment particle sizes were examined. Using the percentages of principal particle sizes, the surface sediments are thus divided into gravelly, sandy, silty and muddy sediments. Additionally, the surface sediments sedimentary areas are classified as continental (or insular) shelf clastic sediments, continental (or insular) slope sediments and abyssal sediments based on water depths and geomorphic features[19]. The surface sediments from the neritic continental or insular shelf regions were further divided into 12 essential categories according to the size composition and the principle of Folk et al.[20]: muddy sandy gravel (msG), gravelly sand (gS), pebbly sand ((g)S), pebbly muddy sand ((g)mS), muddy sand (mS), silty sand (zS), sandy silt (sZ), silt (Z), pebbly mud ((g)M), gravelly mud (gM), sandy mud (sM) and mud (M). Gravelly sediments are typically found on the southwestern and northeastern continental shelves of the D'Urville Island to the north of the Antarctic Peninsula as well as sparsely on the northwestern insular shelf of the South Orkney Islands. Sandy and silty sediments are nearly ubiquitous. They compose the majority of the eastern continental shelf of the Antarctic Peninsula, the majority of the insular shelves of the South Shetland Islands, and a minority of the areas to the south and north of the South Orkney Microcontinent. Muddy sediments are present at the northeastern continental shelf break of the Antarctic Peninsula as well as the majority of the insular shelf breaks and on some of the insular shelves of the South Shetland Islands. Additionally, a large part of the central South Orkney Microcontinent is covered by muddy sediments. Overall, the sediments are diverse and complex and primarily comprise gravel and sand followed by silt and mud. On a cumulative probability curve of sediments (Figure 3), they exhibit rolling and saltation matter with a small fraction of suspended matter. The curves appear in varied forms including two-part, three-part and four-part, display notable coarse/fine cut-off points with coarse components taking up more than 40%, which represents strong hydrodynamic forces.

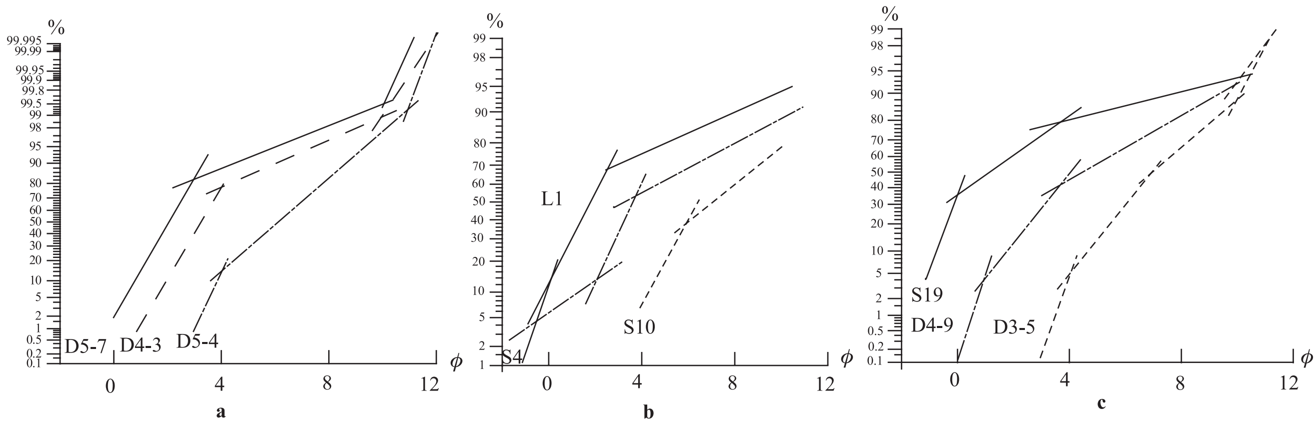

Figure 3 Probability curves of grain size of the surface sediments in the study area (**a**,continental (island) shelf; **b**, continental (island) slope; **c**, abyssal).

Bathyal sediments are typically found on continental and insular slopes and comprise mainly sand and silt, although mud is present at a couple of sites. Pebbles are also observed in the sediment and its content varies. Sediments containing pebbles occur in complicated categories and their cumulative probability curves are actually either two-part or three-part. In general, they comprise mostly saltation matter, followed by suspended matter with only a limited fraction of rolling matter.

Abyssal sediments (>2 000 m water depth) are predominantly fine-grained, usually muddy, followed by sandy sediment. However, a small percentage of gravelly (pebbly) sediment is observed at a couple of stations. The cumulative probability curves are mainly three-partor two-part. In general, these sediments comprise mainly suspended matter, followed by saltation matter with some of them containing no rolling matter, which indicates relatively weak hydrodynamics in the abyssal region.

5.2 Classification and zonation of glacial-marine sediments

Based on previous findings, Anderson et al.[13] defined glacial-marine sediments as deposited over the seafloor through glacier and marine processes and transported by glaciers, ice shelves or related water currents. They contain ice rafted debris, unsorted rock substances of various particle size brought along by glaciers or ice rafts. Divergent environmental aspects have accounted for varying glacial-marine sediments. When correlating the South Antarctic tills and till sheets, Harland[3] proposed the terms "orthotill" and "paratill". The former represents stranded ice shelves deposited after they melted, characterized by non-sorting, no bedding, absence of fossilized marine organisms and little reworking by bottom currents. The latter refers to sediments from melted ice shelves, glaciers or floating ice, characterized by varied levels of reworking of sediment particles by ocean currents and rich in fossilized marine organisms. After examining glacial-marine sediments in the Weddell and the Ross seas, Anderson et al.[3,13] suggested further defining paratills into compound paratills, consisting mainly of fine-grained mud or silt and residual paratills that consist mainly of gravel. These were further divided by Wu et al.[2] from the characterization of glacial-marine sediments in the Bransfield Strait and summarized by Shi et al.[22] (Table 2).

Table 2 Classification of glacial-marine sediments[2, 22]

Glacier-marine sediments				
	Paratill			
Orthotill	Residual paratill	Compound paratill		
	$\mathrm{I_A}$	$\mathrm{I_B}$	$\mathrm{II_A}$	$\mathrm{II_B}$
No bedding, unsorted; contains no fossilized marine organisms, has received little rework by bottom currents	Consists mainly of gravel, with little silt or mud content	Consists mainly of gravel, with silt & mud content	Consists mainly of fine mud & silt, with gravel content	Consists mainly of fine mud & silt, with little gravel content
	Has received different levels of rework by ocean currents, contains rich fossilized marine organisms			

The region selected for our study is geographically unique with the most remarkable climatic and environmental variation in Antarctica over the last century. Injection of melt water from collapsed ice shelves has led to notable environmental changes within the sea, which has had implications for the seafloor sediments and the biotic community inhabiting them. According to the definition of glacial-marine sediments (Table 2) and the classification of glacial-marine sediments in the study area (Table 3), we can assume that the following paratill features characterize the glacial-marine sediments in the study area: type $\mathrm{I_A}$ residual paratills containing little silt and mud; type $\mathrm{I_B}$ residual paratills containing silt and mud; type $\mathrm{II_A}$ compound paratills containing gravel; type $\mathrm{II_B}$ compound paratills containing little gravel. Their size, composition and properties are slightly different from those described in Wu et al.[2] and Shi et al.[22] (Table 3).

Zonation of glacial-marine sediments is subject to environmental parameters such as the shoreline profile, seafloor topography and hydrology. Different types of glacial-marine sediments vary in their media and the associated environmental conditions that represent specific sedimentary settings. In our study, the waters surrounding the Antarctic Peninsula were zoned according to the surface sediment particle size and the classification of glacial-marine sediments (Figure 4), which were used in combination to describe the general distribution of modern glacial-marine sediments.

Residual paratill sedimentary zones (I) are largely found on the continental shelf surrounding the Antarctic Peninsula with small zones on the southern insular shelf of Livingston Island (South Shetland Islands), to the southeastern South Scotia Ridge, off to the west and north of the South Orkney Islands, in the slope and abyssal regions in the central southern South Orkney Microcontinent, and from the continental slope to the abyssal region in the western part of the Weddell Sea. The residual paratill regions largely comprise type $\mathrm{I_B}$ glacial-marine sediments. These sediments typically contain gravel with small fractions of silt and mud

Table 3 Classification of glacial-marine deposits in the marine area surrounding the Antarctic Peninsula

Moraine type			Source	Granularity	Gravel/%	Sand/%	Silt/%	Mud/%	Average grain diameter/Φ
Residual Paratill/%	I	I	WU N Y	Average	33.4	47.3	12.2	7.2	3.61~5.15
				Range	0~77.3	12.7~92.7	1.7~24.4	0~21.9	
		I_A	This Paper	Average	35.9	55.8	6.1	2.2	2.3~3.9
				Range	4.2~79.5	11.5~87.0	4.6~7.5	1.5~3.5	
		I_B	This Paper	Average	8.95	61.9	20.7	8.4	2.04~4.64
				Range	0~59.8	19.9~83.5	6.3~40.7	1.8~22.5	
Compound Paratill/%	II	II_A	SHI F D	Average	1.3	15.5	41.7	41	5.27~9.34
				Range	0~13.8	1.4~52.0	27.7~54.5	18.3~62.8	
			This Paper	Average	1.5	24.1	49.8	24.6	4.41~6.85
				Range	0~11.5	8.1~47.9	29.6~66.7	10.0~43.6	
		II_B	WU N Y	Average	0.4	1.9	71.5	26.2	6.43~7.44
				Range	0~3.2	0.1~6.2	67.9~78.3	16.2~33.9	
			This Paper	Average	0.2	4.3	52.8	33.8	6.10~7.66
				Range	0~3.8	0.4~9.9	24.9~90.8	1.2~69.1	

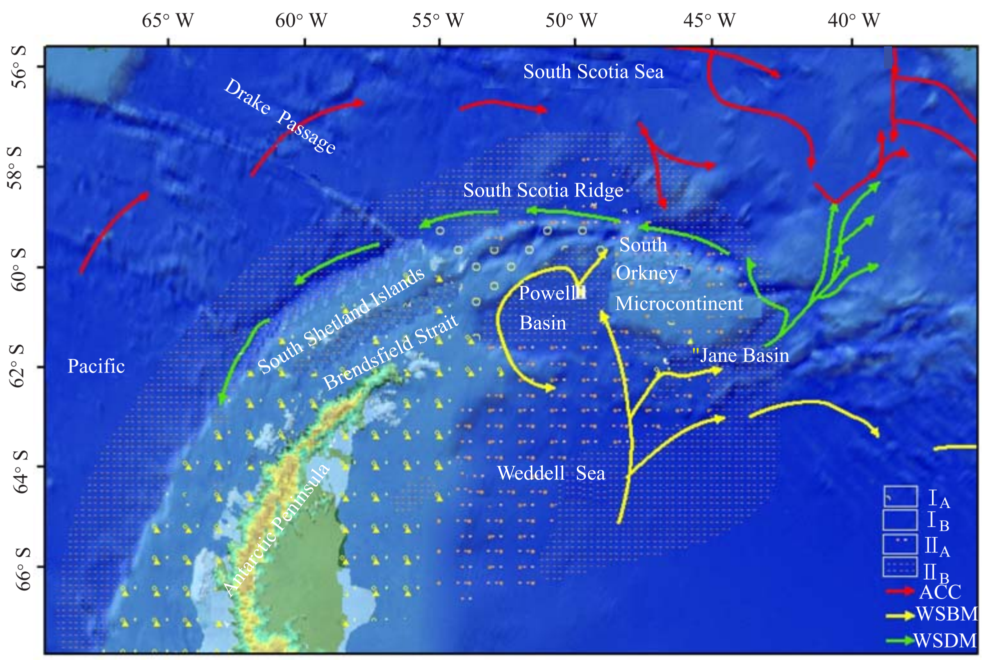

Figure 4 Distribution of glacial-marine deposits in the area surrounding the Antarctic Peninsula.

and are poorly sorted. The type I_A sediments (containing little silt and mud) are mainly found in open marine environments, such as the insular shelves and slopes of D'Urville and Joinville islands to the north of the Antarctic Peninsula, and in most of the Powell Basin. These surface sediments are either thin or absent and poorly sorted and consist mainly of gravel with small mud and silt fractions. They are characterized by complicated origins and intense reworking by ocean currents. These are either where the Antarctic bottom currents and the Weddell Sea currents flow, or a high-intensity cold water mass. Additionally, small regions of type I_A sediments are also found on the western continental shelf of the Antarctic Peninsula and in a small part of the area off the south of the South Orkney Microcontinent.

The type II_A compound paratills (containing gravel) are mostly found from the central northern continental slope to part of the abyssal region of the Weddell Sea in the northeast of the Antarctic Peninsula, the majority of the South Orkney Microcontinent, the southern South Scotia Sea, on the continental shelf off Elephant Island, the southwestern insular slope area in the northern Bransfield Strait, and on the insular shelf and slope south of the King, George, Nelson, and Greenwich islands (South Shetland Islands), as well as a small regionon the eastern continental shelf of the Antarctic

Peninsula. The sediments are mostly mud and silt with a gravel fraction and are poorly sorted. The type II_B compound paratills (containing little gravel) are regularly distributed and dominate in deep waters (>2 000 m). They are common on the continental shelf and in the abyssal region off the western Antarctic Peninsula through to the abyssal region of the South Scotia Sea, the central trough and the southern lower continental slope environment of the Bransfield Strait, in the Powell Basin, the Jane Basin and the majority of the abyssal regions of the Weddell Sea with >3 500 m water depth. This concurs with the features of bathyal-abyssal deposition. Additional small areas are also found on the continental shelf west of the Weddell Sea close to the Antarctic Peninsula and the central platform of the South Orkney Microcontinent. Sediments are mostly mud and silt with little gravel and are poorly sorted.

6 Discussion

Our study area features large bathymetric variation, a complicated topography and diverse current systems (Figure 4). Sedimentary processes are typically influenced by a variety of factors including sources, climate, sedimentary kinematics and organism activity[24-25]. In this section, we discuss the sedimentary setting of the study area particularly the sediment particle size and properties of the glacial-marine sediments with respect to sources, seafloor topography, hydrodynamics and ocean current properties.

The absolute majority of terrigenous clasts off the western Antarctic Peninsula originate from the Antarctic Peninsula and the South Shetland Islands where there is no surface runoff, while most of those in the South Orkney Microcontinent to the northeast come from the South Orkney Islands. According to the particle sorting properties and sediment cumulative curves, and taking into account the texture and structure of the columnar sediments, there should be different levels of turbidity sediments in the Bransfield Strait, the Weddell Sea and the South Orkney Microcontinent[11]. This might be attributed to glacial meltwater, increased ice rafted clastic material and gravity currents. The latter add to the operating capability of the ocean currents, causing the gravity currents to flow down the slope with clastic material and thereby giving rise to turbidity sediments. There has been frequent volcanic activity associated with backarc expansion[27-29] on the Antarctic Peninsula and the South Shetland Islands, as exemplified by the 12 volcanic eruption centers on King George Island that contain huge quantities of cinder, lapillus and pozzolana, and the modern active volcano of Deception Island[30]. As a result of the contribution of volcanic ejecta to the terrigenous clastic material in waters off the northwestern Antarctic Peninsula and on the insular shelf around the South Shetland Islands, it is never ignorable. Volcanic ejecta consist typically of basic basalt and basaltic andesite[31]. The volcanic ejecta around the South Shetland Islands are typically basic volcaniclastic minerals while those along the northwestern Antarctic Peninsula and off Livingston Island are typically intermediate-acidic pyroclastic minerals[32]. Lithologic correlation of the clastic composition in the sediments to the neighboring bedrock reveals that the terrigenous clastic material in the study area are principally products of local deposition that mostly originate from the neighboring continents and islands (i.e., the Antarctic Peninsula and the South Shetland Islands).

Abyssal sediments mainly originate from biogenic material, such as the remains of diatoms, radiolarians and foraminifers, which constitute a non-negligible part of the surface sediments. In deep water, diatoms occur in large quantities even on the northwestern continental shelf of the Antarctic Peninsula where the water depth is <1 000 m. Thus, diatomaceous ooze comprises the sedimentary fine fraction on the continental shelf.

In the polar seas, ice rafting plays a critical role in the transport of clastic sediments[33]. As the study area encompasses the area surrounding the Antarctic Peninsula and is geographically a polar region of the Southern Ocean and there is no surface runoff from the Antarctic Continent to carry sediments into the sea, the main transport processes are ice rafts from glaciers. Ice rafts in Antarctic waters are the primary agents for transporting the bulk of clastic material. Sediments deposited by ice rafts are typically characterized by poor sorting properties and mixed sizes, and are also stochastic. All of the surface sediments of the study area contain different sized pebbles regardless of proximity to shore or water depth. They vary largely in size (Figure 5a) from very coarse to very fine and are mostly poorly to moderately sorted. Their cumulative probability curves appear as four-part, three-part or two-part. Most of the pebbles are angular or subangular with only a small fraction flat or subrounded. Their contents vary significantly (Figure 5) and appear to be irregular. We conclude this is the result of ice rafting, suggesting the large role ice rafted debris plays in sediment deposition of the study area.

The studied area has complicated topography, a variety of ocean currents and, as a result of cold water tributaries from the Weddell Sea, comparatively strong hydrodynamic forces. The ACC[34] flows eastward from the deep waters off the northwestern Antarctic Peninsula through the Drake Passage and branches away towards the South Scotia Sea (Figure 4). WSBW originates from the center of the Weddell Sea and branches northward into two tributaries. One flows westward into the Powell Basin and returns into the Weddell Sea again to the southeast. The other flows eastward into WSDW along the Jane Basin[12] before branching into two additional tributaries, one of which flows eastward around the South Orkney Platform and then makes its way southeastward into the Bellingshausen Sea west of the Antarctic Peninsula along the South Scotia Ridge. In the northwestern Power Basin, a strong tributary of bottom currents from WSBW enters the basin and contacts the surface sediments along the northwestern margin of the Orkney Microcontinent. This adds to the coarse fraction quantity from the northwest of the basin across to the South Scotia Sea (Figures 5a and 5b). Divided roughly from WSDW (Figure 4), the northwestern continental shelf region of the Antarctic Peninsula was heavily exposed to the WSBW, the effect of which coarsens the average sedimentary particle size and makes the region a residual paratill sedimentary zone. The water depth is generally <1 000 m, and surface sediments are typically dominated by sand (Figure 5b) that can be as high as 83% of the total sediment content. Pebble contents vary from none at some stations to 79% at others. Collected pebbles are mostly angular or subangular, suggesting that they have not been substantially worn or transported by waves or currents. In contrast, the surface sediments in the western bathyal-abyssal region are silt and mud dominated. Because of the natural geography, ocean currents have not acted as intensely at the seafloor, thus accounting for the compound paratills containing little gravel with the exception of a couple of stations where a small pebble fraction is present. Surface sediments vary largely in size, suggesting relatively constant sedimentary settings over the recent years as well as a role for ice rafting in the sedimentary processes. In waters off the eastern Antarctic Peninsula, the second tributary of the WSBW was heavily exposed to bottom currents, resulting in an obvious boundary along the bottom currents. The Powell Basin was less exposed to these currents and compound paratills containing little gravel were deposited. The highly undulated area outside the basin has been more heavily exposed to bottom currents, and only a few pebble samples were collected from stations there. The sedimentary bed is either thin or absent, resulting in sharply contrasting type I_A residual paratills. We conclude that it was the exposure to intense bottom currents that accounted for the almost complete absence of fine-grained sediments.

Analysis of sediment particle size demonstrates that most of the samples are moderately to poorly sorted, suggesting that mud and sand were both carried down without sufficient sorting when clastic material was deposited. It appears that ocean currents washed against the continental shelf, upper slope region, shoals and platforms in the western Antarctic Peninsula and accounted for the deposition of residual paratills mainly comprising ice rafted coarse clasts and coarse gravels. In shallow waters like continental and insular shelves, deposition of coarse clasts like gravel prevailed. The intense erosive action of glaciers and ice rafting forced coarse clastic sediments seaward into continental shelf regions, which became residual paratills. Of the deep water sediments, few resulted from ice rafting (Figures 5a and 5b). In deep waters (>2 000 m), such as the Powell Basin and the eastern Weddell Sea, sediments are typically muddy and silty and rich in fine-grained components (Figures 5c and 5d). The topographic dependent variation of sediment types is clear. In the region off the South Orkney Islands, where the topography is more complicated, the sediment type is also more complex; the glacial-marine sediments are comparatively diverse. Although dependent on different water depths, sediments are generally silty towards the outside of the block and sandy from further outside to the slope regions (Figures 5b and 5c). The annular distribution of sediments with topographic positions is also clear.

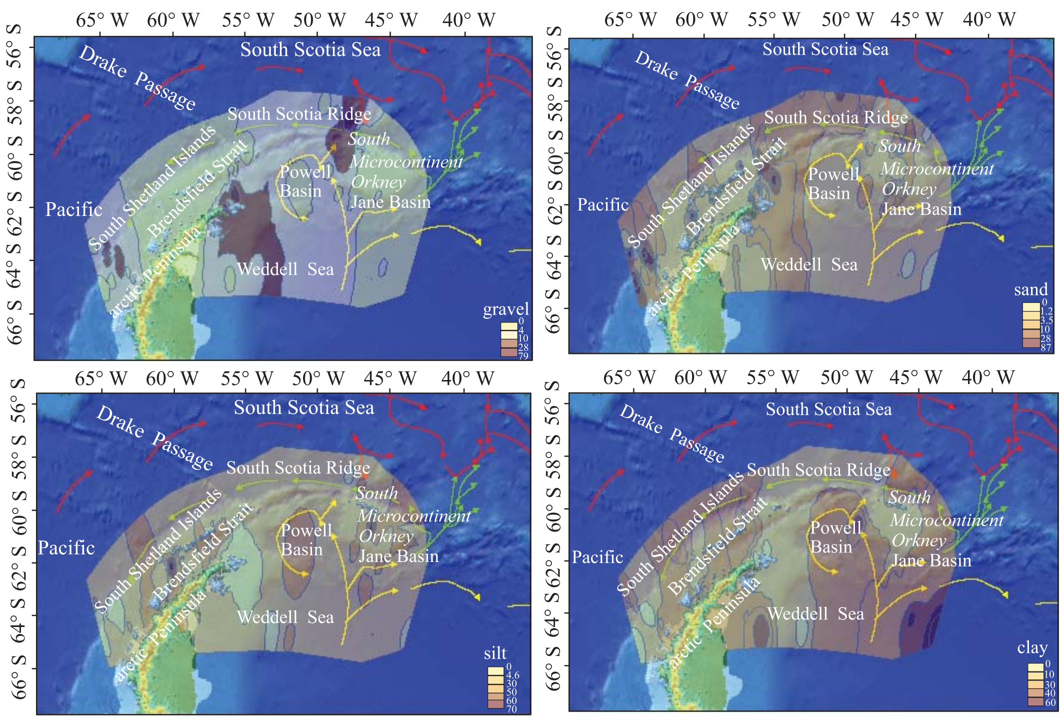

Figure 5 Percentages of each surface sediment composition in the surrounding marine area of the Antarctic (**a**, gravel; **b**, sand; **c**, silt; **d**, clay).

7 Conclusions

Surface sediment particle sizes were examined. Through an analysis of the principal particle size percentages, surface sediments are divided into gravelly, sandy, silty and muddy sediments. As a result of water depth and geomorphic units, they are classified as continental (or insular) shelf clastic sediments, continental (or insular) slope sediments and abyssal sediments[10].

According to how glacial-marine sediments are defined, those surrounding the Antarctic Peninsula exhibit the features of a number of paratills, namely type Ⅰ residual paratills consisting mainly of gravel and type Ⅱ compound paratills consisting mainly of silt and mud. The former is further divided into type I_A residual paratills containing little silt and mud and type I_B residual paratills containing silt and mud; the latter is further divided into type II_A compound paratills containing gravel and type II_B compound paratills containing no gravel. All of these paratills display some regularity in their distribution.

Transport mechanisms for the glacial-marine sediments surrounding the Antarctic Peninsula are predominantly glaciers and ice rafts, which deposit poorly sorted material, including coarse clasts. The fine-grained material migrates away from the glaciers and icebergs after entering the sea. They continue to unload the clastic material frozen inside them during transport. Ocean currents in the study area have great implications for the sediment type and composition. Within the studied area, the percentage of gravel, sand and clay is highly regular, and the type of sediments shows regular variation with the topography.

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