19. PALEOGLACIAL IMPLICATIONS OF COARSE DETRITUS IN DSDP LEG 36 CORES

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INTRODUCTION

One of the primary objectives of Leg 36 was to obtain additional information on the late Cenozoic glacial history of the Scotia Sea-Argentine Basin region by studying ice-rafted detritus in cores of deep penetration. Coarse clastic material of probable glacial origin was recovered at the five most southerly of the six sites drilled, Sites 326-331. The only subbottom samples collected earlier from this region were piston cores recovered during cruises of the Lamont-Doherty vessels *R. V. Vema* and *R. V. Conrad* (Conolly and Ewing, 1965) and of the U.S.N.S. *Eltanin*.

This summary of the distribution and physical characteristics of material believed to be of glacial origin is based primarily on shipboard observations of coarse fraction abundance, texture, and lithology. These studies were later supplemented by standard sieve and pipette grain size analyses that give relative abundances of the coarse sand fraction. In addition, scanning-electron microscopy (SEM) was used to study quartz grain surface textures in samples from Site 328 in order to identify grains of probable glacial origin through application of the criteria of Margolis and Krinsley (1974). We gratefully acknowledge the helpful technical reviews of this paper by Art Ford and Tom Hamilton of the Geological Survey and by Stan Margolis of the University of Hawaii.

DATA

Site 326, Drake Passage

Only one core was attempted at Site 326 whose 50 cm of sediment was recovered at an unknown depth between 0 and 9.5 meters. Abundant sand was present in the core; gravel occurs in a sandy silt matrix in the upper and lower 5 cm of the core and predominates in the core catcher. The gravel, up to 5 cm in maximum dimension, is mainly angular to subrounded and includes a variety of lithologic types (Table 1). A number of clasts show evidence of faceting, although none of these facets are definitely striated. Mixed with the exotic clastic material are abundant manganiferous nodules and rounded basalt pebbles that may be of local origin. Ice rafting is the most plausible mechanism for supplying a substantial fraction of the coarser sand and possibly 25% of the gravel. The microfauna indicates a Quaternary age for the sediment (see Site Report, this volume).

Polymictic faceted clasts in the surficial veneer of sediment place this site within the limits of rafting by icebergs during the part of the Quaternary represented by the core. The compositions of the nonbasaltic and nonmanganiferous pebbles are compatible with a mixed plutonic, metamorphic, felsic volcanic, and sedimentary source terrane which could have existed in southern South America, Antarctica, or both.

TABLE 1
Composition and Volume Percent of Granules and Pebble Size Clasts in Selected Core-catcher Samples

Clast Lithology	Sample 326-1, CC	327A-1, CC	328-1, CC	328A-1, CC
Manganese nodules	65	55	Tr	42
Siliceous concretions		21		
Shale, siltstone, argillite		10	20	17
Sandy mudstone	3	5	Tr	
Arkosic sandstone		3		
Rhyolite porphyry, quartz latite, pumice	8	4	15	29
Graywacke	2	2		
Garnetiferous biotite, granite		<1		
Granite, granodiorite, quartz monzonite	7	<1	10	1.5
Olivine basalt, basalt andesite	10		10	1
Quartz-mica schist, phyllite, gneiss	3		5	2
Metavolcanics (chloritic)	2			
Quartzite, quartzose sandstone	Tr		15	2
Granite porphyry			25	
Gabbro		Tr		Tr
Quartz				2

Sites 327, 327A, Eastern Falkland Plateau

The upper 10 meters at this site consist of muddy sand and gravel with a 2-meter interbed of diatomaceous clay. Gravel is concentrated mainly in the surface section, but is present in lesser amounts throughout this interval. It consists mostly of authigenic manganiferous nodules, glauconite, siliceous concretions, and about 30% angular to rounded rock fragments of variable composition to 7 cm in maximum dimension (Table 1). Some of the clasts are faceted, and a few of the soft shales are striated, possibly as a result of the drilling operations.

Size grading occurs within some of the sand and gravel units, but this could result from core handling. The sand fraction is predominantly glauconite with lesser amounts of quartz and feldspar. A few faceted pebbles found in the interval between 10 and 20 meters are believed to be contaminants from the upper part of the hole, as they invariably occur in disturbed zones within the core and are associated with large manganiferous nodules that were probably originally at or near the sea floor. An abundant siliceous microfauna in the section containing in situ ice-rafted detritus ranges in age from Pliocene to Holocene (see Site Report, this volume).

Coarse exotic detritus recovered at this site indicates that icebergs were intermittently present over the Falkland Plateau from probable Pliocene to Holocene time (based on diatom zonation). The provenance was dominantly sedimentary with subordinate amounts of felsic volcanics and minor amount of granitic rocks and gabbro, including one large garnet-bearing biotite granite pebble. Distinctive reddish-brown arkosic sandstone clasts that constitute an estimated 2% of the pebble population are unlike sandstones known to occur in southern South America. They possibly derive from the Beacon Supergroup of Antarctica, which, where exposed in East Antarctica, includes extensive arkosic continental clastic rocks of Devonian and Triassic age (Barrett et al., 1972). Further speculation regarding the late Cenozoic paleoglacial history recorded at this site does not appear to be warranted due to the attenuated section containing ice-rafted material, the lack of paleontological zonation within this section, and indications of core disturbance and contamination.

Site 328, Malvinas Outer Basin

At Site 328 three holes were drilled through, or partly through, a 13.5-meter-thick near-surface sequence of ooze containing probable ice-rafted sand and gravel that extends downward into the late Miocene *Denticula hustedtii* diatom Zone (see Site Report, this volume). Beneath this pebbly interval, the ooze contains sand in amounts to a few percent to a subbottom depth of 48.1 meters, below which sand content drops to 0.2% or less. Some of the quartz sand grains exhibit textural features considered to be characteristic of material of glacial transport. The distribution of coarse clastic sediment in the upper parts of these holes is shown in Figure 1.

In the upper 13.5 meters, sand and gravel are disseminated throughout the ooze and occur as discrete thin beds to 5 cm thick. The pebbles and granules include a wide variety of lithologic types of continental affinities, as illustrated by Samples 328-1, CC and 328A-1, CC (Table 1), which include pebbles to 5.3 cm in maximum dimension. Typically, the clasts are angular to subangular, a few pebbles clearly show faceting and striations characteristic of abrasion by glacial transport. In overall abundance and lithology, Samples 328-1, CC and 328A-1, CC differ in several respects. Most notable is the virtual absence of manganese nodules in Hole 328 and their abundance in Hole 328A. Dropstones in 328 are of diverse lithologies, whereas those in 328A are predominantly felsic volcanics and argillaceous sedimentary rocks. Ferromanganese nodules occur throughout this interval, many nucleated on pebbles. Pebble distribution in the cores corresponds closely to the distribution of abundant sand (>10%) as shown in Figure 1. Below about 13.5 meters, sand and manganese nodules are sporadically present, but there are no clasts larger than sand size.

Dropstone lithology suggests a mixed provenance that includes crystalline plutonic and metamorphic rocks of diverse composition, texture, and metamorphic grade and volcanic rocks, dominantly rhyolitic in composition, but also andesitic and basaltic. Sedimentary rocks are mainly dark colored graywacke, siltstone, shale, or mudstone with less common clean quartz-rich sandstone or quartzite. Most of the rock types found could have originated in either Patagonia or the Antarctic Peninsula. Particularly noteworthy is the occurrence of very well sorted quartzose sandstone, the most likely source for which are strata similar to the Beacon Supergroup of the Transantarctic Mountains (Barrett et al., 1972). The presence of hematite-cemented quartzose sandstone and rare reddish-brown shale suggests derivation from a red-bed sequence in Antarctica as red beds are widely exposed in the Pensacola Mountains and in northern Victoria Land (Barrett el al., 1972) but are not known to occur in Patagonia. Sparse faceted and striated clasts among the dropstones suggest that at least some of the transport was along the base or margins of the glaciers.

Grains from the sand fraction of 15 samples from Holes 328 and 328B were examined under the scanning electron microscope to determine the occurrence and stratigraphic lower limit of quartz grains of glacial origin. Samples selected from the least deformed parts of cores were dried and weighed prior to further treatment. They were then gently disaggregated in a dilute Calgon solution, washed over a 62 μm sieve, and the coarse fraction dried and weighed. Sand grains and siliceous microfossils made up most of the residue. The number of sand grains per gram of sediment in the sample was estimated under the binocular microscope by counting (Table 2) before representative fractions of the residues were mounted on aluminum plugs, coated with platinumpalladium, and examined under a Cambridge S-410 scanning electron microscope equipped with an EDAX energy-dispersive X-ray analytical system. Under the SEM, the diameter of the largest grain in the sample was determined (Table 2) and selected grains were examined in considerable detail after X-ray analysis to insure that they were indeed quartz. In all, 54 grains were studied and the presence or absence of a variety of grain surface morphologic features noted, both at magnifications of less than 1000× and more than 1000× (Figures 2 and 3). Results are shown in Table 3.

All samples examined contained quartz sand grains bearing the surface morphologies commonly attributed to glacial action (Table 3): extreme angularity, high relief, large conchoidal fractures, and parallel steps. Evidently glacially sculptured grains were available for transport to the Malvinas Outer Basin area as early as the Oligocene (see Site Report, this volume). We doubt, however, that this implies rafting by glacial icebergs occurred as early as Oligocene time, for reasons elaborated upon below.

There are contrasts in the data bearing on paleoglacial history of the upper Miocene and younger parts of the core on the one hand, and the earlier Miocene and Oligocene parts on the other hand. For example, from the late Miocene upwards, dropstones are abundant (Figure 1), sand percentages are high both in mechanical analyses (Figure 1) and in grain counts

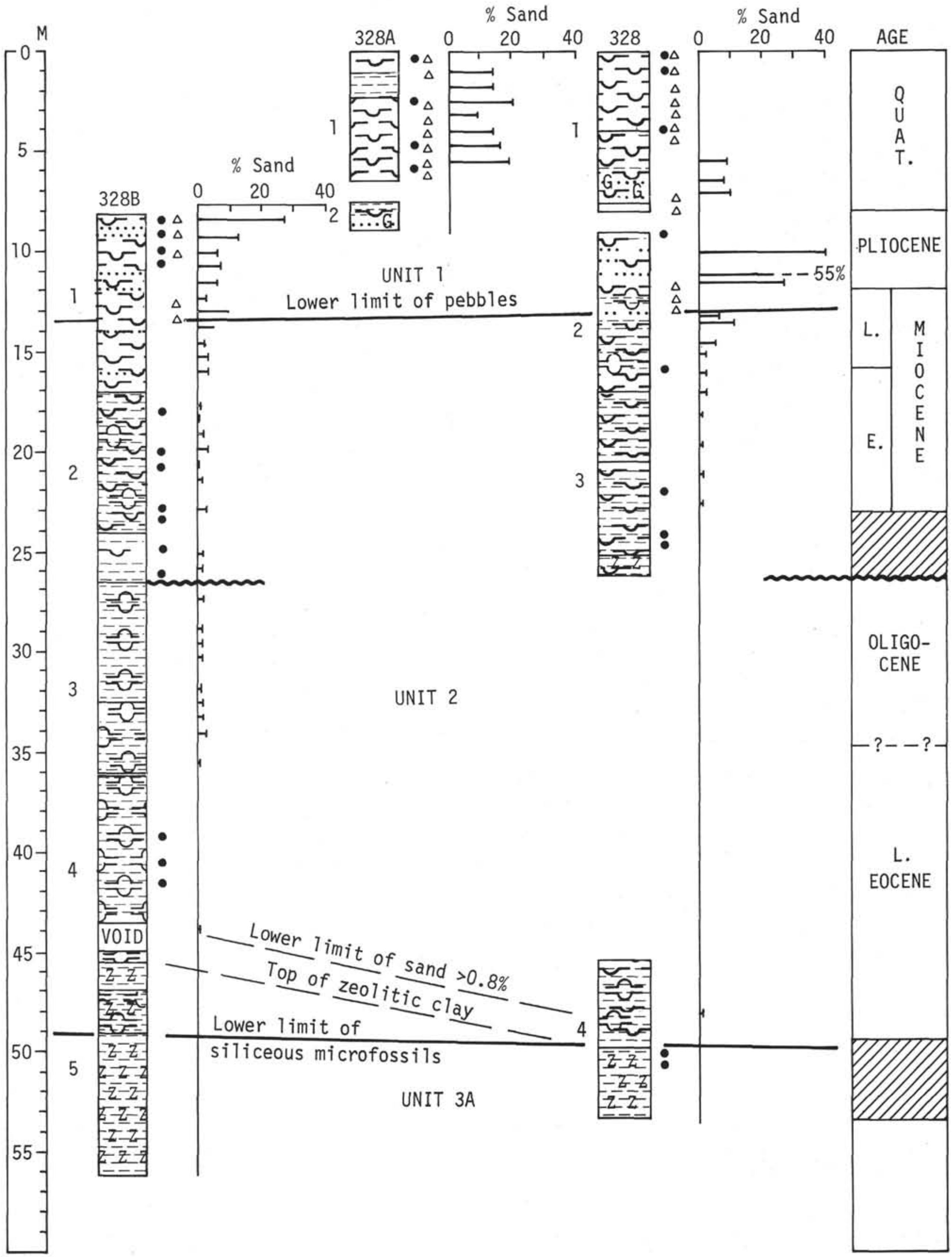

Figure 1. *Stratigraphic correlations and coarse fraction distribution in the upper part of holes drilled at Site 328. Distribution of manganiferous nodules indicated by solid dots, dropstones by triangles, and sand by bar graph.*

TABLE 2
Grain Size and Abundance of Quartz Sand Grains in Samples from DSDP Leg 36, Holes 328 and 328B

Sample (Interval in cm)	Age	Wt. of Dried Whole Samples (g)	Wt. of Dried Samples >62 μm Diameter (g)	Percent >62 μm Diameter	Maximum Grain Size (μm)[a]	Estimated no. Sand grams per dry gram[b]	Siliceous Microfossils (A=abundant R=rare
Hole 328							
1-1, 70-72	Pleistocene	0.5469	0.0568	10	450	–[c]	A
Hole 328B							
1-2, 64-71; 73-75	Late Miocene-Pliocene	0.8131	0.1321	16	450	–[c]	A
1-4, 110-115	Late Miocene-Pliocene	0.2853	0.0143	5	230	4200	A
1-4, 135-140	Late Miocene-Pliocene	1.2700	0.1262	10	300	–[c]	A
1-5, 130-135	Late Miocene-Pliocene	1.1062	0.1967	18	400	–[c]	A
2-2, 125-140	Early Miocene	0.4441	0.0378	9	250	340	R
2-4, 135-140	Early Miocene	0.2511	0.0223	9	200	120	R
2-6, 135-140	Early Miocene	0.3251	0.0844	26	120	450	R
3-2, 130-135	Oligocene?	0.5314	0.0240	5	100	230	R
3-4, 130-135	Late Oligocene	0.7652	0.0218	3	100	180	A
3-6, 117-123	Late Oligocene	0.7976	0.0190	3	100	30	A
4-2, 125-130	Early Oligocene	0.7915	0.0177	2	80	15	A
4-5, 50-55	Early Oligocene	0.3206	0.0110	3	–	20	A

[a]Estimates from SEM grain mounts of sediment fraction >62 μm size.

[b]Includes all sand size grains regardless of composition.

[c]Siliceous microfossils too abundant for reliable estimate of number of sand grains.

(Table 2), and the maximum size of quartz grains is relatively large (200 to 400 μm). Below the latest Miocene, gravel dropstones are absent, sand abundance appears to decrease by a factor of 10, and maximum grain size decreases by a factor of 2 or more.

We interpret these contrasts in paleoglacial data as resulting from different modes of transportation of glacially sculptured quartz grains. The late Miocene and younger record, with an abundance of sand and gravel dropstones, provides convincing evidence of iceberg rafting. Glacier-fashioned quartz grains in older strata at Site 328 may have initially reached the sea primarily by wind transport. These grains could subsequently have been transported to the Malvinas Outer Basin by ocean currents or, perhaps, on seasonal pack ice. The presence of strong bottom currents during this period is clearly attested to by bottom erosion and winnowing at Site 328 since the early Oligocene. If the glacial grains in the older strata were deposited by drifting icebergs, why were not coarse sand and pebbles also encountered and why is the abundance of sand-sized grains so low (no major departures from an approximately linear sedimentation curve are noted for Oligocene and younger sediments at the site—see Site Report, this volume)?

The initiation of glacial iceberg rafting of pebbles and sand in late Miocene time at the Malvinas Outer Basin is in excellent agreement with the late Miocene onset of iceberg rafting in subantarctic latitudes in the southwestern Pacific Ocean south of New Zealand (Margolis, 1975). Nearer the Falkland Plateau in the southeastern Pacific Ocean, however, glacial sand grains have been found in piston cores of sediments as old as Eocene and Oligocene (Margolis and Kennett, 1971) and ice-rafted pebbles as old as early Oligocene occur in the southern Ross Sea (Hayes and Frakes, 1975). One possible interpretation placed on these occurrences in Paleogene sediments is that continental glaciation began somewhat earlier in East Antarctica than in West Antarctica (Margolis, 1975).

The paleoglacial data reported here from sediments of Oligocene and early Miocene age on the Falkland Plateau seem to support the concept of development of glaciers in East Antarctica at least as early as Oligocene time. The size distribution, however, suggests to us that ice shelves did not develop until the late Miocene and that winds were the agent primarily responsible for transporting glacially sculptured fine-grained quartz into the sea.

Site 329, Eastern Falkland Plateau

The upper 4.5 meters at Site 329 consists of diatom ooze rich in pebbles, sand, silt, and clay. This interval contains a Pleistocene to Holocene microfauna (see Site Report, this volume). Sand-sized detritus is present lower in the hole to Core 6 (56 m), which is of late Miocene age, and pebbles were found intermittently in the interval 170 to 455 meters, which penetrates strata as old as Oligocene.

Pebble-size clasts, to 6.5 cm in maximum dimension, include granite, felsic volcanics, pink sandstone, quartzite, graywacke, metasandstone, metasiltite, and chloritized gabbro. Many of the clasts are angular to subangular and appear to be faceted; a few are striated. These surface features are suggestive of glacial transport. Pebbles encountered below 4.5 meters depth occur in a matrix of soft, pure diatomaceous ooze below a long interval of nondetrital ooze. Consequently, they are believed to be downhole contaminants that probably fell to the bottom of the hole periodically as a result of enlargement of the soft upper part of the hole due to high water pump pressures. The small amount of

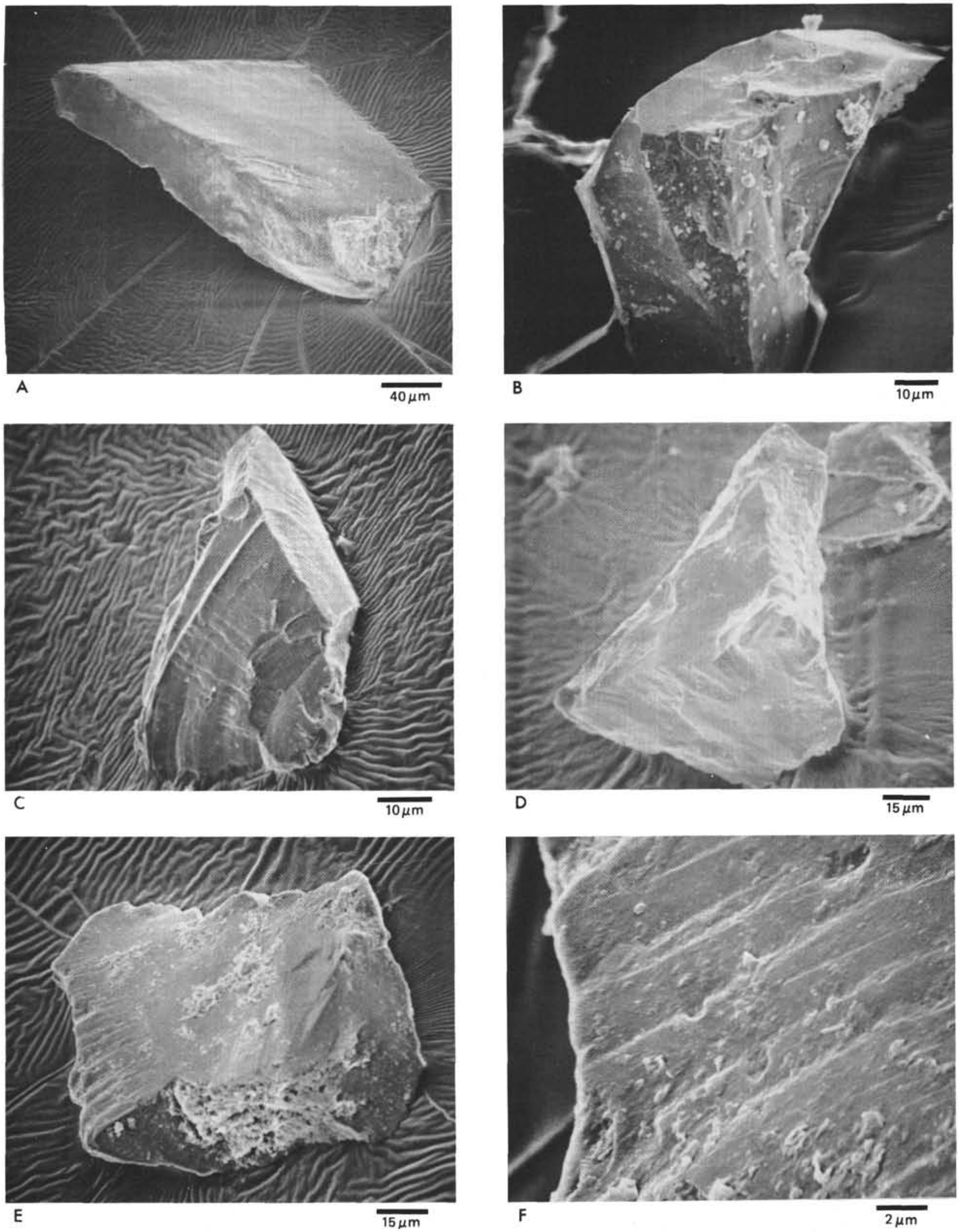

Figure 2. *SEM photographs of glacially sculptured grains from the Falkland Plateau. (A) Quartz with large and small conchoidal fracture surfaces. Sample 328B-1-4, 110-115 cm. (B) Quartz grain with very high relief and large conchoidal fracture surfaces. Sample 328B-2-4, 135-140 cm. (C) Angular, high-relief quartz with well-defined conchoidal fractures and parallel steps. Sample 328B-2-4, 135-140 cm. (D) High-relief quartz grain with small conchoidal fractures; grain appears to have a patina of precipitated silica. Sample 328B-2-6, 135-140 cm. (E) Quartz grain with upper surface consisting of a single conchoidal fracture. Sample 328B-2-6, 135-140 cm. (F) High magnification view of left grain margin of grain shown in E. Detail of parallel steps in fracture and U-shaped solution or abrasion pits. Sample 328B-2-6, 135-140 cm.*

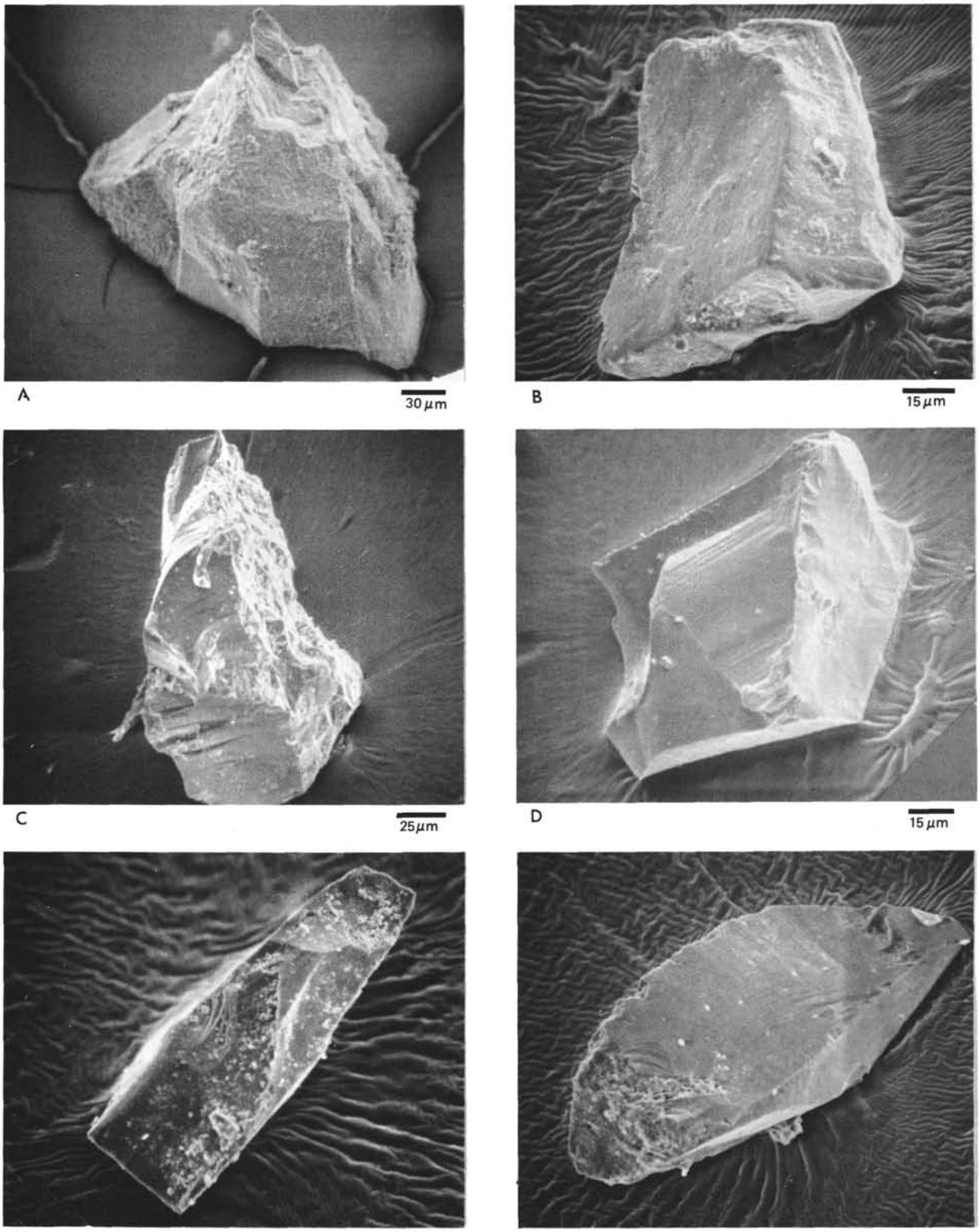

Figure 3. *SEM photographs of glacially sculptured grains from the Falkland Plateau. (A) High-relief quartz grain with layer of precipitated silica on larger fracture surfaces. Sample 328B-3-2, 130-135 cm. (B) Quartz grain bounded by conchoidal fracture faces overlain by a smooth coating of silica. Sample 328B-3-2-, 130-135 cm. (C) Small conchoidal fractures on a quartz grain. Sample 328B-3-6, 117-123 cm. (D) Quartz grain with large conchoidal fractures. Sharp projections of the left margin formed by intersecting conchoidal fractures would not be likely to survive transport as bedload in an aqueous medium. Sample 328B-3-6, 117-123 cm. (E) Subrectangular quartz grain ("cleavage" fragment?) exhibiting small conchoidal fractures. Sample 328B-5-2, 10 cm. (F) Quartz grain with upper surface formed by a single large conchoidal fracture. Sample 328B-5-2, 10 cm.*

TABLE 3
Textural Features of Quartz Sand Grains for Site 328[a]

Sample (Interval in cm)	No. Quartz Grains Analyzed on SEM	Straight or Curved Grooves	Variation in Size of Conchoidal Breakages	High Relief	Rounding and/or Solution	Large-scale Conchoidal Breakages	Percent Commi- nution Debris	Straight and/or Curved Grooves	Arc Steps (percus- sion?)	Parallel and/or Subparallel Steps (Shear Stress?)	Small-Scaled Conchoidal Fractures	Upturned Plates	Precipi- tation Platelet	Cleavage Flake	Pitted Surfaces	Irregular Indentations (Etching?)	V's[b]
328-	5				X		10						X	X	X	X	
1-1, 70-75				X	X	X	30	X					X	X			
		X	X	X	X			X					X			X	
				X	X	X	<10				X		X			X	
							15						X		X	X	
328B-	6				X		20								X	X	
1-2, 64-71;			X		X	X	40				X		X			X	
73-75					X		50	X	X	X					X	X	
					X	X	30								X	X	
			X		X					X	X		X		?		
		X			X		25	X		X	X			X			
328B-	9		X		X	X	15			X	X		X				
1-4, 110-115					X	X	<10	X	X				X		X	X	
					X	X	20						X		X	X	
					X		10			X		X	X			X	o?
					X												
				X	X	X	10				X		X				u?
					X		10								X	X	
		X		X			<10			X	X						
				X	X	X	<10			X						X	
328B-	2				X	X				X	X		X		X	X	
1-4, 135-140					X	X	10						X		X	X	
328B-	5				X	X	<10						X			X	
1-5, 130-135			X	X	X		20		X							X	
			X	X	X	X	<10				X		X				
				X	X		<10	X							X	X	
				X	X	X	<10	X							X	X	
328B-	5			X	X	X	60					X	X		X	X	
2-2, 135-140					X	X	70						X	?	X	X	
					X		60					X	X		X	X	
			X	X	X	X	20	?		X			X			X	
				X	X	X	30				X		X		X	X	
328B-	3			X	X	X	30			X	X		X			X	
2-4, 135-140				X	X	X	25	X			X					?	
			X	X		X	10			X	X					X	
328B-	6			X	X	X	35		X				X		X	X	
2-6, 135-140					X		70					X			X	X	
					X		50										
			X	X	X	X	10					?				X	
			X	X	X		<10		X		X						
				X	X		60						X	X	X	X	
328B-	6	X			X		<10	X			X			X			u
1-2, 130-135											X						
				X	X	X	<10	X					X			X	
				X		X	<10				X						
					X	X	30		X				X		X	X	
					X		15						X		X	X	
328B- 3-4, 130-135	1		X	X	X	X							X		X	X	
328B-	3		X	X		X	20		X		X		X			X	
3-6, 117-123			X	X	X	X	20		X	X	X		X			X	
			X	X	X	X	<10	X	X	X	X		X			X	
328B- 4-2, 125-130	1				X	X						X	X	X	X	X	

[a]Criteria selected from: Krinsley and Donahue 1968; Krinsley and Doornkamp, 1973; Setlow, and Karpovich, 1972; Whalley and Krinsley, 1974; Margolis and Krinsley, 1974.
[b]U = unoriented; o = oriented.

sand in the section below 4.5 meters could have been transported and deposited by bottom currents, or by wind, or could have been introduced during drilling as downhole contaminants.

At Site 329, as at nearby Site 327, the thin interval containing ice-rafted dropstones appears to be at least as old as Pleistocene and extends into the Holocene.

Site 330, Eastern Falkland Plateau

Site 330, located close to Sites 327 and 329, did not sample the near-surface sediment and therefore does not provide data relevant to the paleoglacial history.

Site 331, Northern Argentine Basin

A single surface core, from 0 to 8.5 meters, was taken at Site 331. The core is composed almost entirely of Quaternary clay and silt with rare sand grains and no coarser clasts. As there is no evidence to indicate that any of this sediment is of glacial origin, it is likely that the site lies beyond the limits of Quaternary ice rafting.

CONCLUSIONS

Interpretations that can be drawn from Leg 36 samples regarding the paleoglacial history of the Scotia Sea-Argentine Basin region are severely constrained by the small number of sites drilled, and where drilled, by incomplete sections, poor recovery, and downhole contamination of cores. The available data, nonetheless, indicate that ice-rafted detritus reached as far north as the Falkland Plateau (50°S latitude) in about late Miocene time, that ice-rafting in the Falkland Plateau area probably has continued intermittently since the late Miocene. and that the most likely source for much of the clastic material throughout late Cenozoic time is Antarctica. Further, the distribution of glacially sculptured fine-grained quartz sand at Site 328 suggests the possibility that wind-transported glacial sediment from Antarctica was being deposited in the sea as early as Oligocene time and that some of this fine sand was subsequently carried into the Malvinas Outer Basin, most probably by bottom currents.

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