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12. PROVENANCE OF PLIOCENE–PLEISTOCENE ICE-RAFTED DEBRIS, LEG 145, NORTHERN PACIFIC OCEAN[1]

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ABSTRACT

Petrographic examination of Pliocene–Pleistocene dropstones from the Northwest Pacific Ocean (ODP Sites 881–884) and from the Gulf of Alaska (ODP Site 887) reveals two contrasting clast populations.

The Northwest Pacific Ocean dropstones consist largely of a suite of relatively pristine arc-derived basaltic-andesites and andesites and associated volcaniclastic rocks. Also present are older(?) variably metamorphosed felsic volcanic rocks and related volcaniclastic rocks, diverse mixed provenance sandstones, and argillite or phyllite. Plutonic crystalline rocks are a very minor component. The presence of both chert and rhodochrosite-rock clasts suggests that the dominant direction of ice rafting was from the western Bering Sea down the eastern coast of the Kamchatka Peninsula, and not eastward from across the Sea of Okhotsk.

In marked contrast, the Site 887 dropstones are less diverse, being composed predominantly of arkosic and mixed-provenance sandstones, arenaceous quartzo-feldspathic foliated metasediments, semischists, and schists. Felsic and basic intrusives and high-grade metamorphic rocks constitute a subordinate contribution. Basaltic volcanic rocks are rare. Cherts are absent. The overall provenance suggested by the dropstones at Site 887 is from southeastern Alaska.

INTRODUCTION

Dropstones were sampled from drill cores recovered at Ocean Drilling Program (ODP) Sites 881–884 and 887 (Fig. 1). This was done in order to determine the provenance or source areas of the dropstones by studying their petrography. No dropstones were observed at Sites 885 and 886, their location being beyond the zone of ice rafting in the Pacific Ocean. None of the dropstones exceed 9 cm and most are less than 5 cm. Almost all are subrounded to rounded. The oldest dropstone intervals are dated (Shipboard Scientific Party, 1993a, b) at approximately 6 Ma at Hole 882B (Section 145-882B-26H-3) and at approximately 4.5 Ma at Hole 887A (Section 145-882B-14H-2). In addition to the dropstones sampled from the cores, bulk samples of small pebble dropstones (less than 1 cm) were obtained from "washed-in" materials recovered at four intervals at Site 881 and at one interval at Site 887. The washed-in materials are not well constrained stratigraphically, having fallen in from the sides of the holes, usually during core recovery.

PREVIOUS STUDIES

Relatively few data exist on the petrography of dropstones recovered from North Pacific cores. From Deep Sea Drilling Project (DSDP) Leg 18 in the Gulf of Alaska and off the eastern Aleutians, von Heune et al. (1973) reported a preponderance (95%) of slates and greywackes, with only a minor contribution of granite, granodiorite, mica schist, and metavolcanic rocks. These authors considered this clast population to be clearly derived from Alaska.

On the succeeding DSDP Leg 19, through the western Aleutians, Fullam et al. (1973) supplied few detailed petrographic data of dropstones, and simply referred to lonestones of pumice, argillites, greywackes, and volcanic material. However in an earlier pioneering study of the terrigenous sand fraction recovered from Northwest Pacific *Vema* and *Conrad* piston cores of siliceous oozes, collected in the 1960s, Conolly and Ewing (1970) recognized a predominance of older altered and younger fresh andesitic to basaltic rock types, with a lesser contribution of red siltstones and sandstones, greywackes, quartzites, granites, and gneisses. This work contains the only previous photomicrographs published of Pacific Ocean ice-rafted debris (IRD). The most recent data are of Krissek et al. (1985), who in assessing the abundance of ice-rafted debris west of Japan, at DSDP Sites 579 and 580 (DSDP Leg 86), recognized mudstone, granite, andesite, and basalt.

Although the data are limited, the areal distribution of dropstones and finer grades of IRD in the Northwest Pacific is also of interest. Conolly and Ewing (1970) drew attention to the decrease in concentration of IRD in their cores both northward and southward from a region centered at about 165°E, 48°N (their Fig. 5), about 300 km east of the Sea of Okhotsk and the southern tip of Kamchatka. Accordingly they suggested a Siberian source to the west for the IRD maximum concentration. Later DSDP data (Legs 19 and 86) and that collected by Leg 145 confirm this pattern (Site 881 cores contain the highest concentration of IRD), and this again suggests that the main transport direction of ice-rafted pebbles (and all other IRD) in the Northwest Pacific Ocean was eastward from the Siberian Okhotsk-Kamchatka region of Northeast Asia (Shipboard Scientific Party, 1993a).

Interpretations of the source of the ice-rafted debris have important implications for the reconstruction of Pliocene and Pleistocene glaciers on Kamchatka and the mainland of Northeast Siberia. If the Okhotsk Sea source postulated by Conolly and Ewing (1970) and Shipboard Scientific Party (1993b) is correct, then extensive glaciers must have fronted on the Siberian and the west Kamchatkan shores. However, Flint's (1972) generalized Pleistocene reconstruction about the Sea of Okhtosk shows only very limited glaciers at sea level, focused mainly in the north in the vicinity of Tauy Bay near Magadan and around the head of Gizhiga Bay in the Shelikov Gulf (Fig. 2). Anderson (1981, their fig. 1-4) shows a similar reconstruction about the Sea of Okhotsk for the late Pleistocene. The Pleistocene reconstructions of Arkhipov et al. (1989) do record some early and middle Pleistocene glaciers at sea level on the west coast of the southern Kamchatka Peninsula. If the source of the tongue or concentration of ice-rafted debris in the Northwest Pacific can be shown to be the shores of the Sea of Okhotsk, then a major reappraisal of the Pliocene/Pleistocene glacial geology will be necessary. None of the reconstructions show areas of Pleistocene tidal glaciers large enough to provide large volumes of detritus that might be ice-rafted out of the Sea of Okhotsk. On the other hand, all paleo-

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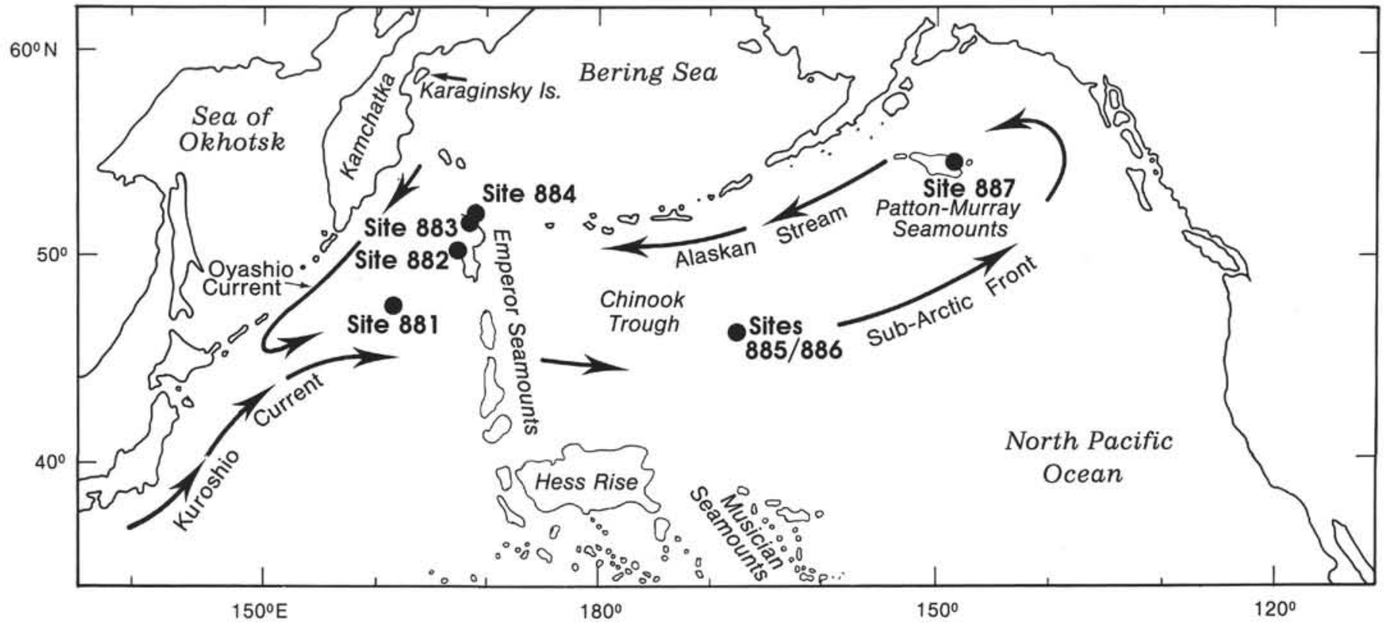

Figure 1. Site map and distribution of major North Pacific Ocean current systems.

glacial reconstructions appear to indicate large areas of glacier ice near or at sea level on the eastern coast of Kamchatka.

The Site 887 dropstones, and all other Gulf of Alaska dropstones, are assumed following the studies of Rea and Schrader (1985) to be derived largely from Alaska. This present study then conveniently falls into two parts, one dealing with the Northwest Pacific sites off the Kurile Arc and Kamchatka Peninsula (Sites 881–884); and the other part dealing with Site 887 on the Patton-Murray Seamounts in the Gulf of Alaska.

NORTHWEST PACIFIC DROPSTONES

Thin sections were prepared of the 24 stratigraphically well-constrained dropstones recovered from the cores at Sites 881–884. In addition, 205 thin sections were prepared from the washed-in small pebbles retrieved from Cores 145-881C-7H, -25X, and -36X. 229 dropstones were identified microscopically and classified into 12 broad petrographic groups (Table 1 and Fig. 3). Groups 1 to 4 appear relatively pristine in thin section, whereas the other seven groups exhibit either cataclastic or ductile deformation, or else extensive metamorphic mineralogical reconstitution. One remaining small group consists of granitic rocks.

In an effort to emphasize the salient provenance signature of these Northwest Pacific dropstones, the above 12 petrographic groups were reduced to seven (Fig. 4) for the reasons set out below. The geological soundness of this procedure is not without question, but given the small individual samples, there are few practical alternatives.

Groups 2, 3, and 4, which are composed of relatively pristine and compositionally similar arc-derived or arc-associated volcaniclastic rock types (Fig. 5), were combined on the assumption that collectively these three groups record the glacial erosion of relatively young "mid-Cenozoic" (late Paleogene–Neogene?) volcanic arc rocks and their related sedimentary sequences. As a single group, portrayed as mid-Cenozoic in Figure 4 and totalling 34.5% of the clasts, these rocks contrast with the tectonized or otherwise mineralogically metamorphosed felsic to intermediate arc volcanic rocks (16.2%), similarly altered diverse sandstone types (collectively totalling 21.4%), fine-grained metasediments, and cherts. These latter four groups we interpret as having a more complex geological history and are therefore probably derived from geologically older (i.e., pre-mid-Cenozoic) terranes.

To help justify the assumptions that our "younger" volcanic and associated volcaniclastic dropstones can be regarded as mid-Cenozoic or possibly older Neogene, and probably mostly arc-derived, we compared the chemical compositions of some of this material with the volcanic ashes in the same cores, derived from the Kurile-Kamchatka arc system (see Cao et al., this volume).

The bulk compositions (major and trace elements) of 12 of the most pristine volcanic dropstones were analyzed by a combination of inductively coupled plasma source mass spectrometry (ICP-MS, see Cao et al., this volume, for analytical procedures) and for Al_2O_3 by atomic absorption spectrophotometry. Because of the loss of volatile silicon fluoride during sample preparation for the ICP-MS technique, we had to resort to calculating SiO_2 as the difference between the major and minor element oxide total (excluding SiO_2) and 100%. We note however, that the SiO_2 content of two standard rocks determined in this way were in agreement with published values to within 0.5 wt%. We also determined $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values for 10 of these dropstones (see Cao et al., this volume, for analytical procedures). All analytical data are reported in Table 2.

The majority of the analyzed dropstones are andesitic, only two appear to contain >63 wt% SiO_2 (i.e., dacitic) and 1 has <52.5 wt% SiO_2 (i.e., basaltic). The majority of the samples are Medium-K according to Gill's (1981) classification, the exception being the basaltic sample, which is High-K. In terms of Miyashiro's (1974) criterion, seven of the samples are calcalkaline and four are tholeiitic. The majority of the samples (excluding Samples 145-881C-7H-1, 0–20 cm, pebble 145, and 145-883C-2H-6, 130–131 cm) have low TiO_2, and most (excluding Sample 145-881C-7H-1, 0–20 cm, pebble 179) have high Al_2O_3.

Chondrite-normalized rare earth element (REE) and other trace element abundances are displayed in Figures 6 and 7. Major points of note are that the systematics of the trace element abundances of the majority of the dropstones are similar to island arc andesites with high Ba/Nb and Sm/Ti, and the REE abundances of some of the samples match some of the ash groups (a) to (l) identified by Cao et al. (this volume). For example, Sample 145-881C-7H-1, 0–20 cm, pebble 152, is similar to group (d) or (e), Sample 145-881C-7H-1, 0–20 cm, pebble 148, is similar to group (h), and Samples 145-881C-7H-1, 0–20 cm, pebble 011, and 145-881C-7H-1, 0–20 cm, pebble 104, match the overall abundances and fractionation pattern of group (i) of

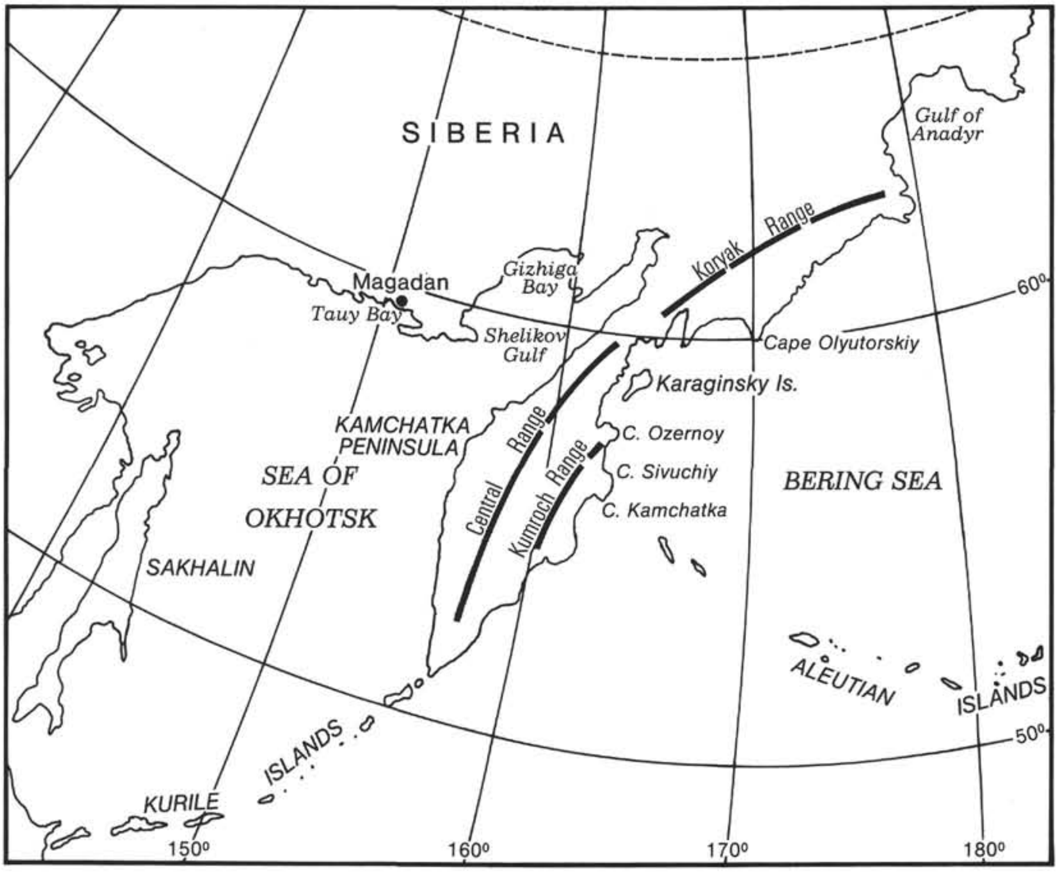

Figure 2. Locality map of the Sea of Okhotsk-Kamchatka-western Bering Sea region.

Table 1. Petrographic clast-type percentages (229 clasts), Sites 881–884.

	Petrographic group	Sites 881–884 (% total clasts)
1	Rhodochrosite-rock containing diatomaceous and/or hyaline shard admixtures.	7
2	Andesites, basic andesites, and basalts; little alteration.	17
3	Volcaniclastic matrix-bearing sandstones; predominantly andesitic-basic andesitic provenance; little alteration.	5.7
4	Argillites; some exhibit indistinct remnant silt-grade vitroclastic textures (i.e., altered ashes).	11.8
5	Felsic to intermediate volcanic or shallow intrusive rocks; originally predominantly hyaline; extensive fine-grained metamorphic alteration.	16.2
6	Felsic to intermediate volcaniclastic sandstones; predominantly andesitic provenance; extensive fine-grained metamorphic alteration.	16.2
7	Lithic sandstones; mixed felsic volcanic and fine-grained metasedimentary provenance(?); extensive fine-grained metamorphic alteration.	1.7
8	Quartzose sandstones; fine grained, subangular; ferruginous cements.	3.5
9	Phyllites and semischists, exhibiting fracturing and/or microfolding.	9.6
10	Chert. Variable purity, fractured, and commonly recrystallized.	7.0
11	Basic plutonic rocks; extensively altered (amphibolitic) gabbroic and doleritic rocks.	3
12	Felsic plutonics; granodioritic.	1.2

the ashes. In addition, the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ of the dropstones overlaps the isotopic range of the ashes (Fig. 8).

There are some major differences however, between the major and trace element characteristics of the dropstones and the ashes. The abundant Pliocene and younger vitric ashes from the Kurile Arc and Kamchatka Peninsula source in the cores from Sites 881–884 are predominantly rhyolitic (Cao et al., 1993). Thus most of the analyzed dropstones are unlikely to be simply the proximal (vent or volcanic carapace) facies equivalents of the ashes from Sites 881–884 and may represent either older volcanic material, or relatively nonexplosive near-vent components of eruptive cycles leading to the ash emission. Secondly, a number of the dropstones are characterized by positive Eu anomalies of varying magnitude, whereas most of the ashes have negative anomalies. It appears that a number of the dropstones may be cumulatively enriched in plagioclase. And finally, the high field strength elemental (e.g., Nb, Ta, Hf, and Zr) abundances of Sample 145-883C-2H-6, 130–131 cm, are more like ocean island (i.e., hot spot) than arc-derived material.

Taking this compositional data into account, and noting both in these clasts and the associated volcaniclastic dropstones the relative lack of tectonic overprinting and mineralogical metamorphism, we regard them, albeit tentatively, as of mid-Cenozoic age.

The abundance of volcanic and volcaniclastic rock types, and the relative lack of plutonic intrusives and high-grade metamorphic rocks, seems in the first instance to provide few clues as to the precise provenance of the dropstones from within the region of the Sea of Okhotsk and the Kurile and Kamchatka arcs of Eastern Siberia or Northeast Asia. However, we believe two of the clast categories are significant in this respect: Group 7, the varied cherts, and (to a lesser extent) Group 1, the rhodochrosite-rock ($MnCO_3$) clasts (Figs. 4, 9, 10).

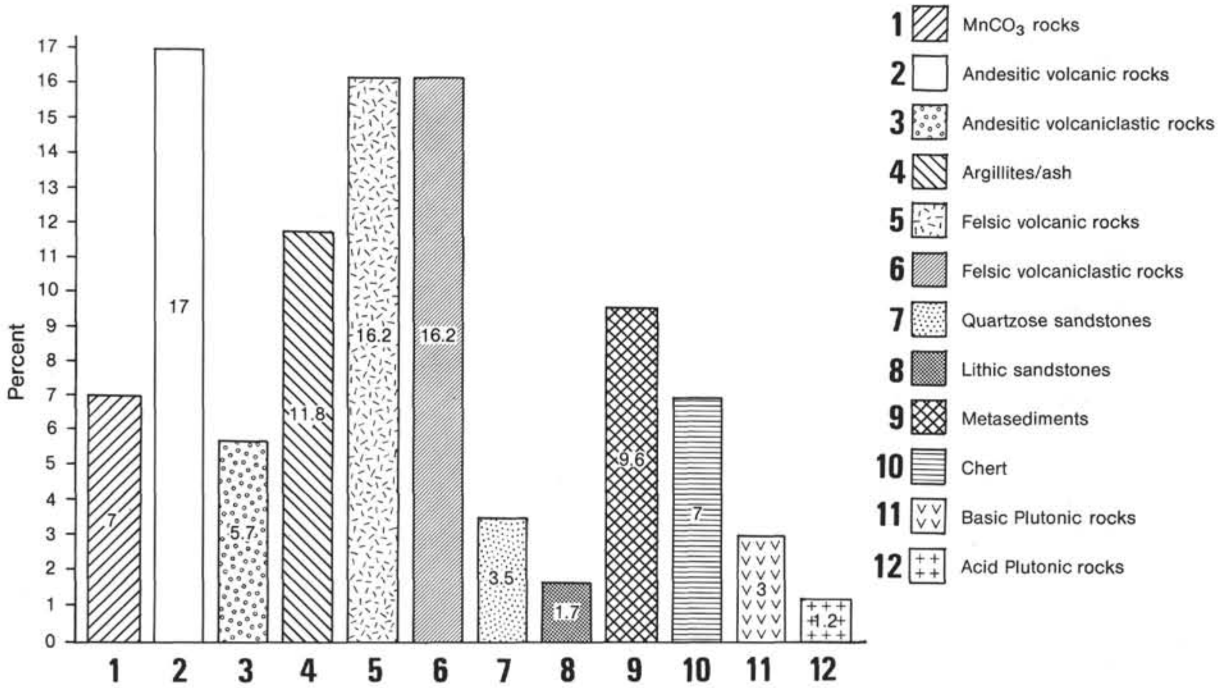

Figure 3. Petrographic clast-type percentages (229 clasts), Sites 881–884.

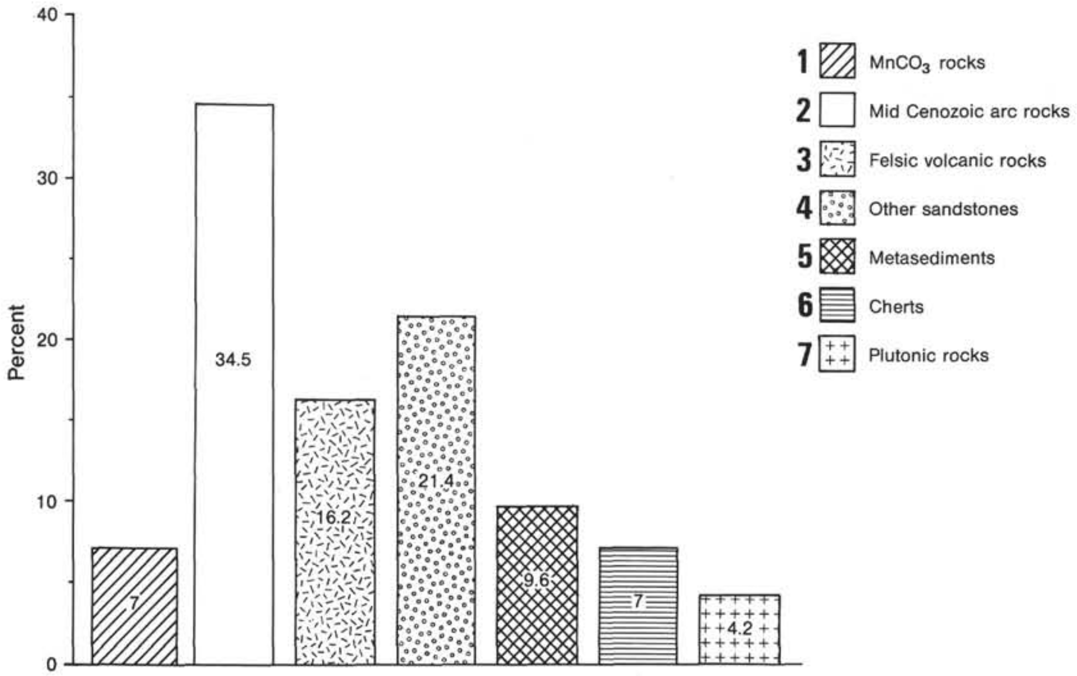

Figure 4. Clast-type percentages of reduced petrographic groupings, Sites 881–884.

Discussion

In assessing the provenance of the Northwest Pacific clasts three factors merit consideration.

1. Regional geology of Northeast Asia and in particular the Sea of Okhotsk-Kamchatka Peninsula region.
2. Configuration of Pliocene–Pleistocene Siberian glaciers.
3. Relative influence on Pliocene–Pleistocene iceberg transport of the Kuroshiro and Oyashio currents.

Published regional maps indicate Northeast Asia to be geologically intricate (Parfenov et al., 1993; Natal'in, 1993). Parfenov et al. (1993) recognized and summarized lithologically no fewer than 68 structural blocks and terranes and 22 subterranes between 140°E and 180°E. There are, as might be expected, few common rock types that do not

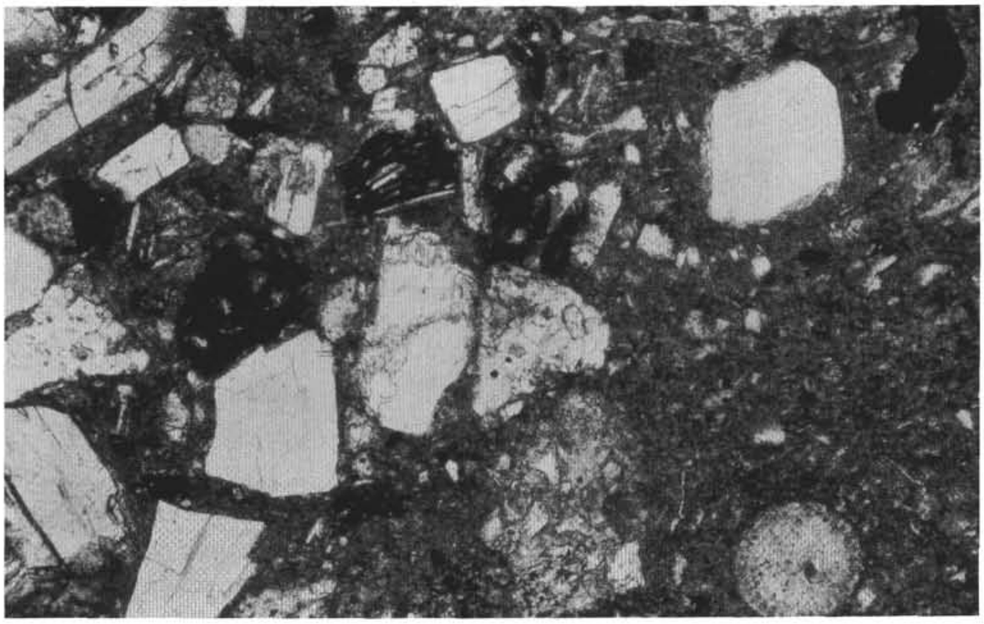

Figure 5. Dropstone of microfossil-bearing (bottom right) matrix-rich andesitic volcaniclastic sandstone (Sample 145-883C-2H-4, 115–117 cm). Varied light and dark volcanic lithic fragments (including a pyroclastic one, bottom center-right) and fresh plagioclase grains occur in the abundant matrix, which includes abraded vitric debris. Field width is 2 mm.

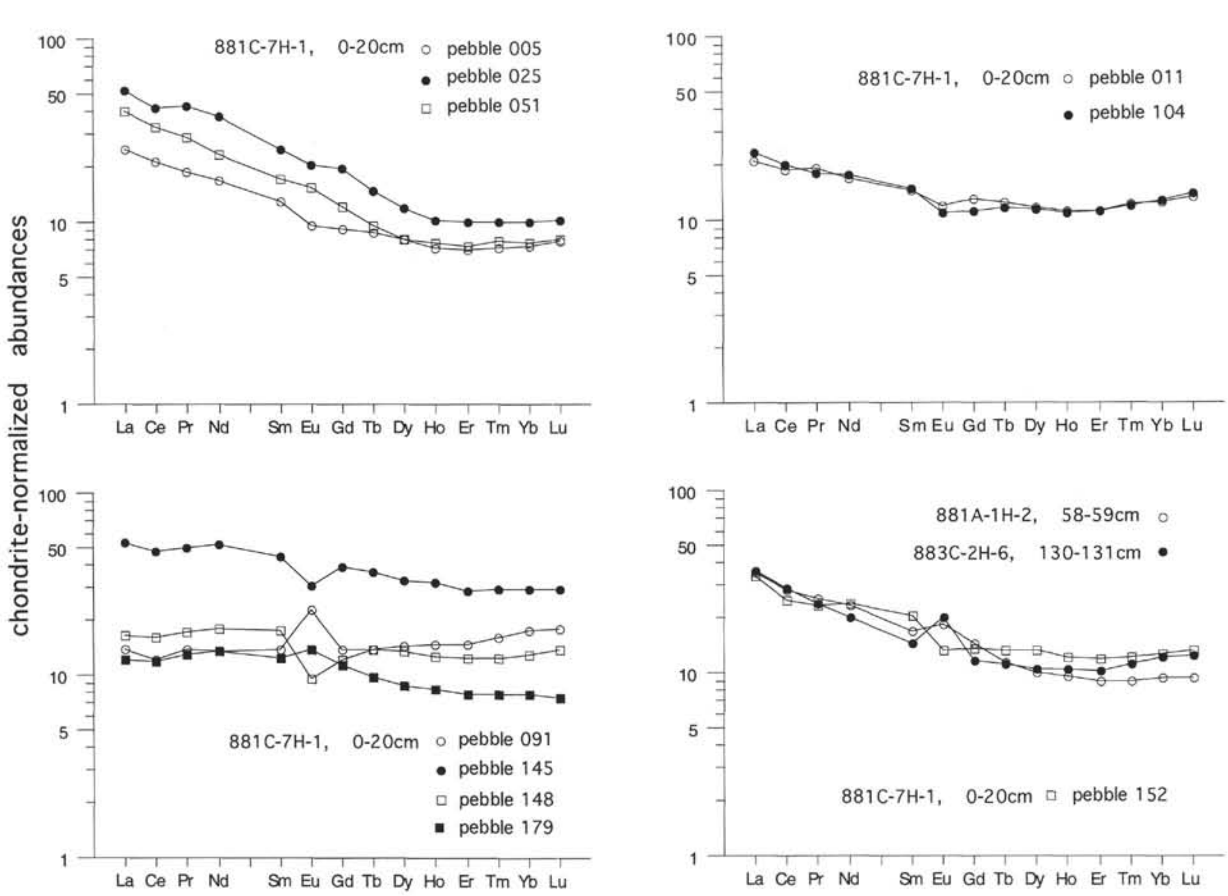

Figure 6. Chondrite-normalized rare earth element abundances of relatively pristine dropstones of volcanic texture. Normalizing factors after Sun and McDonough (1989).

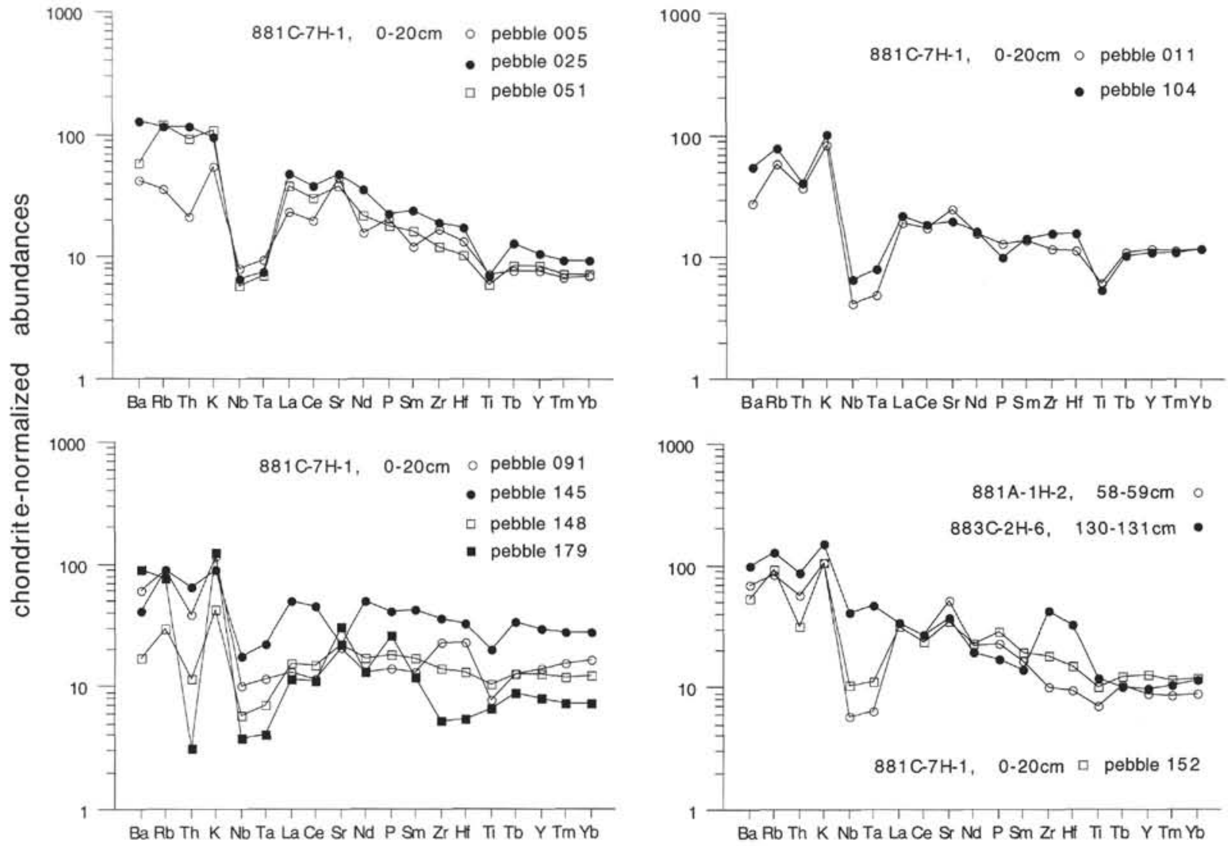

Figure 7. Chondrite-normalized abundances of selected trace elements of relatively pristine dropstones of volcanic texture. Normalizing factors after Sun and McDonough (1989).

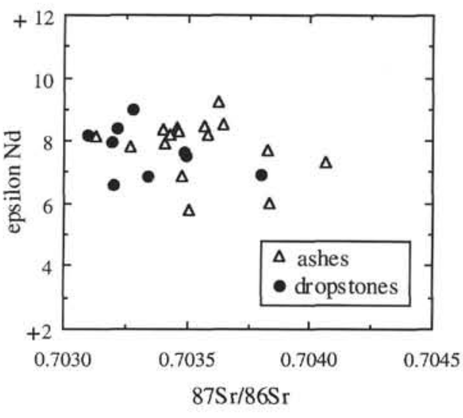

Figure 8. Epsilon Nd (deviation in parts in 10,000 from a reference value of 0.512638) of $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ (measured values, without age corrections) of selected dropstones from Sites 881 and 883 compared with ashes from Sites 881–884 (see Cao et al., this volume).

occur in at least some of these structural units. However, a striking feature of this rather remarkable compilation is that cherts and siliceous argillites, are listed as common rock types in only five terranes or subterranes. These five are all distributed in a broken line, or belt, running along the eastern side of the Kamchatka Peninsula northeastward into and beyond the Koryak Range, to west of the Gulf of Anadyr (Fig. 2). From north to south, the chert-bearing terranes and subterranes recognized by Parfenov et al. (1993) are the mid-Cretaceous–Paleocene Valaginsky subterrane (eastern ranges of Kamchatka, Ozernoy Peninsula and Karaginsky Island), Maastrichtian–Eocene Stolbovskoy island arc terrane of Cape Sivuchiy, Senonian–lower Paleogene Ukelayat subterrane comprising the southeastern part of the Koryak Range, and, to the north, the Proterozoic–Cretaceous Pekul'ney terrane and Permian–Mesozoic Kuyul subterrane (see Fig. 1 of Parfenov et al., 1993).

In a different type of study that is essentially a tectonic synthesis of Kamchatka and the southern part of the Koryak Range, based upon both geological and geophysical data, Geist et al. (in press) recognized that "most of Kamchatka is an amalgamation of far-travelled terranes of different origins" and that "the volcanic rocks that constitute most of the terranes have an island arc affinity." However, in their stratigraphic summary (see their Fig. 2) these authors clearly identified sequences of Cretaceous and Paleogene chert and shaly chert (siliceous argillite?) along the eastern side of Kamchatka in the Cape Olyutorsky region, on Karaginsky Island, and at both Cape Kamchatka itself and the Kumroch Range close by to the west. These localities coincide, at least in part, with the chert-bearing Valaginsky subterrane, the Stolbovskoy terrane, and the Ukelayat subterrane listed by Parfenov et al. (1993). Clearly, consideration of the regional distribution of the chert-bearing sequences strongly suggests the derivation of the ice-rafted chert dropstones to be from along the eastern coast of the Kamchatka Peninsula. This view is further supported by the generally accepted idea that widespread Pliocene–Pleistocene glacier ice reached sea level along this same coast.

Chert-bearing sequences occur in the Cretaceous Sorachi-Yego structural belt of Hokkaido (Kiminami et al., 1992; Hirano et al., 1992), but both the relatively minor outcrop area and the apparent absence of glaciers reaching sea level during Pliocene–Pleistocene time precludes abundant chert-pebble rafting from that source.

The remarkable rhodochrosite-rock dropstones (Figs. 9 and 10) must be considered. We have found so far no reference to indurated strata of this petrographic type in Northeast Asia or, for that matter, anywhere! We do note however, that Gladenkov et al. (1991), in sum-

Table 2. Major and trace element data for relatively pristine dropstones of volcanic texture from Sites 881 and 883.

Hole, core, section:	881A-1H-2	881C-7H-1	881C-7H-1	881C-7H-1	881C-25X-1	881C-7H-1	881C-7H-1	881C-7H-1	881C-7H-1	881C-7H-1	881C-7H-1	883C-2H-6
Interval (cm):	58–59	0–20	0–20	0–20	0–7	0–20	0–20	0–20	0–20	0–20	0–20	130–131
Pebble:		5	11	25	51	91	104	145	148	152	179	
Major elements (wt%)												
SiO_2	56.24	60.88	59.31	58.78	60.12	65.83	65.84	55.38	52.97	54.94	47.86	59.96
TiO_2	0.72	0.74	0.64	0.72	0.61	0.8	0.56	2.05	1.08	1.03	0.68	1.22
Al_2O_3	16.3	16.77	17.22	16.39	18.1	16.55	17.31	15.11	17.37	17.52	13.06	16.72
Fe_2O_3	8.26	6.34	7.16	7.75	5.71	5.18	4.65	12.63	10.09	9.68	11.39	7.18
CaO	9.09	7.86	8.38	8.12	7.79	4.4	5.27	7.69	9.94	7.93	11.68	6.22
MgO	5.36	3.99	3.34	4.31	3.49	1	1.36	3.04	5.25	3.12	11.32	3.63
MnO	0.15	0.1	0.14	0.13	0.12	0.15	0.1	0.2	0.17	0.18	0.19	0.13
Na_2O	2.2	2.36	2.5	2.23	2.35	4.33	3.34	2.24	2.36	3.81	1.8	2.68
K_2O	1.46	0.77	1.19	1.33	1.52	1.63	1.45	1.27	0.6	1.5	1.75	2.09
P_2O_5	0.23	0.21	0.13	0.23	0.18	0.14	0.1	0.41	0.18	0.29	0.26	0.17
Trace elements (ppm)												
Li	7.57	4.91	6.69	7.32	5.48	3.17	13.48	15.03	9.88	8.18	17.18	16.53
Sc	23.12	16.35	24.27	22.22	18.57	16.64	12.81	28.39	19.87	22.1	27.01	17.75
V	265.31	169.16	217.58	228.49	208.14	35.66	79.83	331.06	289.61	218.16	326.5	150.24
Cr	78.43	82.67	40.01	75.74	14.43	4.43	7.7	4.15	47.44	8.45	294.46	44.9
Co	25.83	28.23	35.75	24.7	100.53	6.48	13.18	263.86	31.65	18.81	46.91	18.76
Ni	30.93	41.17	30.73	30.04	102.69	2.55	7.39	249.9	35.54	5.71	154.18	30.7
Cu	99.01	23.78	61.95	66.98	28.19	7.6	26.85	67.78	147.32	20.19	58.32	15.14
Zn	61.75	59.65	59.38	64.09	57.98	79.67	57.38	120.23	81.39	86.95	72.81	72.24
Ga	9.79	7.8	6.37	15.34	9.39	9.79	8.18	8.36	5.87	9.28	10.23	13.02
Ge	1.22	1.03	1.18	1.53	1.15	0.09	0.15	2.45	1.44	0.89	1.09	1.11
Rb	29.59	12.7	20.61	41.03	42.12	31.14	27.43	31.01	10.3	32.6	26.37	45.37
Sr	609.42	535.26	297.19	578.54	460.92	240.69	240.09	262.33	257.75	414.23	363.8	433.51
Y	17.86	15.34	23.51	21.55	17.24	27.61	22.12	58.58	25.8	25.7	16.19	19.8
Zr	69.18	117.06	81.67	132.71	84.27	153.87	109.57	244.05	94.28	122.87	36.34	293.75
Nb	2.06	2.85	1.49	2.31	2.06	3.49	2.33	6.08	2.01	3.7	1.31	14.53
Mo	0.96	1.62	1.42	2.32	1.92	1.56	1.9	2.4	1.1	1.89	0.42	1.96
Cs	1.43	0.29	1.28	1.85	2.45	0.95	1.91	1.62	0.34	1.02	0.42	1.52
Ba	481.52	293.21	193.92	885.27	407.73	425.2	377.1	282.65	118.11	363.35	620.45	678.49
La	11.01	7.66	6.46	16.09	12.45	4.33	7.2	16.37	5.12	10.46	3.75	11.06
Ce	23.05	17.33	15.27	33.59	26.56	9.9	16.3	38.84	13.01	20.33	9.65	23.55
Pr	3.08	2.29	2.34	5.22	3.5	1.68	2.19	6.11	2.1	2.82	1.6	2.9
Nd	13.91	10.09	10.21	22.57	13.86	8.22	10.55	31.53	10.72	14.34	8.17	12.11
Sm	3.31	2.52	2.82	4.87	3.36	2.69	2.91	8.65	3.43	3.96	2.4	2.85
Eu	1.35	0.7	0.86	1.49	1.13	1.66	0.79	2.27	0.7	0.97	1.02	1.47
Gd	3.75	2.36	3.33	5.04	3.16	3.55	2.9	10.11	3.18	3.48	2.94	2.99
Tb	0.54	0.41	0.58	0.69	0.45	0.65	0.55	1.73	0.65	0.63	0.46	0.52
Dy	3.21	2.58	3.75	3.83	2.6	4.65	3.7	10.65	4.36	4.24	2.85	3.36
Ho	0.69	0.52	0.81	0.74	0.56	1.06	0.79	2.31	0.91	0.87	0.6	0.75
Er	1.88	1.49	2.35	2.09	1.55	3.1	2.36	6.15	2.6	2.51	1.66	2.13
Tm	0.29	0.23	0.39	0.32	0.25	0.52	0.38	0.95	0.4	0.39	0.25	0.36
Yb	1.95	1.53	2.61	2.11	1.6	3.68	2.66	6.14	2.7	2.63	1.63	2.56
Lu	0.3	0.25	0.42	0.33	0.26	0.58	0.44	0.95	0.44	0.42	0.24	0.4
Hf	1.91	2.67	2.31	3.54	2.08	4.57	3.21	6.63	2.64	3.03	1.08	6.59
Ta	0.13	0.19	0.1	0.15	0.14	0.23	0.16	0.44	0.14	0.22	0.08	0.95
Pb	7.5	6.06	6.69	18.21	9.69	8.76	9.42	8.72	4.27	5.35	5.32	9.42
Th	2.41	0.9	1.55	4.92	3.95	1.64	1.71	2.7	0.48	1.33	0.13	3.68
U	0.85	0.4	0.55	2.27	1.2	0.75	0.65	1.32	0.23	0.83	0.16	1.71
$^{87}Sr/^{86}Sr$	0.702979	0.703101		0.703497	0.703201	0.703343	0.703485	0.703805	0.703216		0.703282	0.703198
$^{143}Nd/^{144}Nd$	0.512975	0.513058		0.513023	0.512975	0.512991	0.51303	0.512992	0.513067		0.513098	0.513046
Epsilon Nd	6.6	8.2		7.5	6.6	6.9	7.7	6.9	8.4	9.0	8.0	

Notes: SiO_2 determined by difference; Al_2O_3 determined by atomic absorption analysis; all Fe reported as Fe_2O_3.

marizing the Pliocene sequence of Karaginsky Island, referred to (p. 240) "tuffaceous diatomite" and "interbedded ash tuffs" with "numerous carbonate concretions" in Unit 11 of their Limimtevayamim Suite (i.e., Group or Formation). Similar reference is made in the overlying Unit 12 to "diatomaceous tuffaceous siltstone" strata and "interbedded volcanic ash and lenses of carbonate concretions." In both units, the carbonate concretions range up to 0.5 m in diameter. We suspect from their textures in thin section that the rhodochrosite-rock dropstones are fragments of these same carbonate concretions, derived from both the diatomaceous and/or tuffaceous Pliocene strata.

Hein and Scholl (1978) speculated that some southern Bering Sea carbonate-rich beds from DSDP Leg 19 may have formed from the replacement of pyroclastic units. They envisaged the initial deposition of calcite, siderite, rhodochrosite or dolomite in fractures and pore spaces; followed by obliteration of the original vitroclastic textures through subsequent recrystallization and grain growth. Conceivably drilling brecciation of such beds could produce fragments of rhodochrosite-rock, which could easily be interpreted as ice-rafted dropstones. We would maintain that this is not the origin of the Leg 145 rhodochrosite-rock dropstones because of the following two points.

1. Some of these dropstones contain only a diatom admixture (Fig. 9) and lack any pyroclastic input.

2. Two of the rhodochrosite-rock dropstones were sampled in situ in core (Samples 145-883A-1H-4, 27–28 cm, and 145-884B-31X-4, 74–78 cm) and are not from the washed-in gravels recovered at Site 881.

For these reasons, the overall evidence suggests to us that the ice-rafted pebbles were transported from the western Bering Sea, southward past Karaginsky Island, and southward from along the west coast of the Kamchatka Peninsula. We find no compelling evidence to suggest a major contribution from across the Sea of Okhotsk and through the Kurile Arc. The concentration maximum of ice-rafted debris found at Site 881, and its decrease to the north and south, indicates to us both a longer residence time for ice bergs in this vicinity, and increased melt-out from them owing to the meeting of the Oyashio current with the warmer northeastward-travelling Kuroshio current (Fig. 1).

SITE 887 DROPSTONES

In all, 59 individual dropstones were examined microscopically from Site 887. The 23 sampled directly from the core are well constrained stratigraphically. In addition, thin sections were made of 36 small (<10 mm) pebbles obtained from the "well rounded pea gravel"

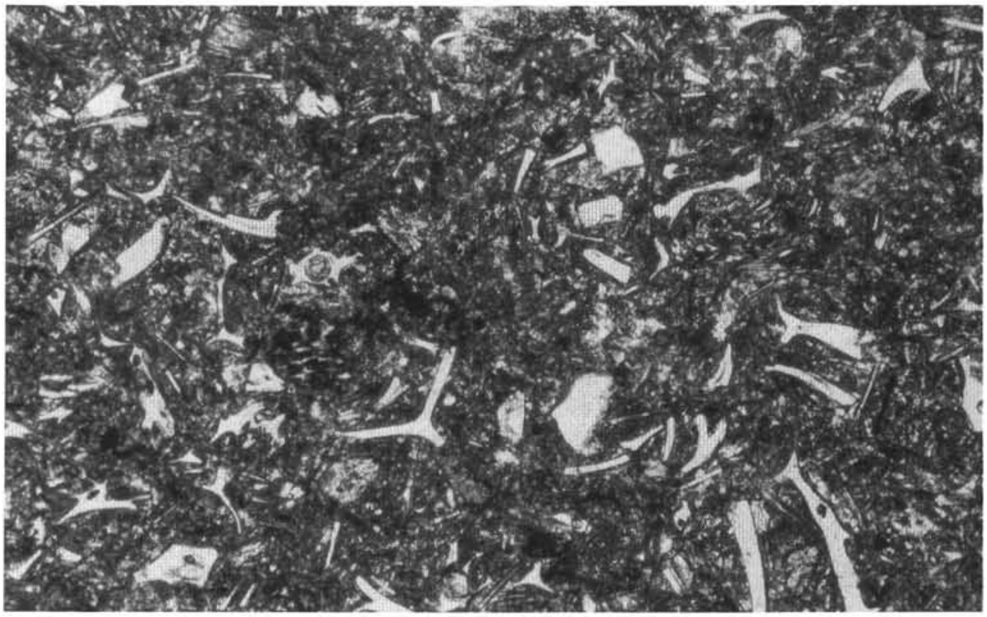

Figure 9. Rhodochrosite-rock dropstone (Sample 145-881C-7H-1, 0–20 cm, pebble 002: washed-in gravel). Isotropic opaline diatom fragments are dispersed in microcrystalline rhodochrosite. Field width is 0.5 mm.

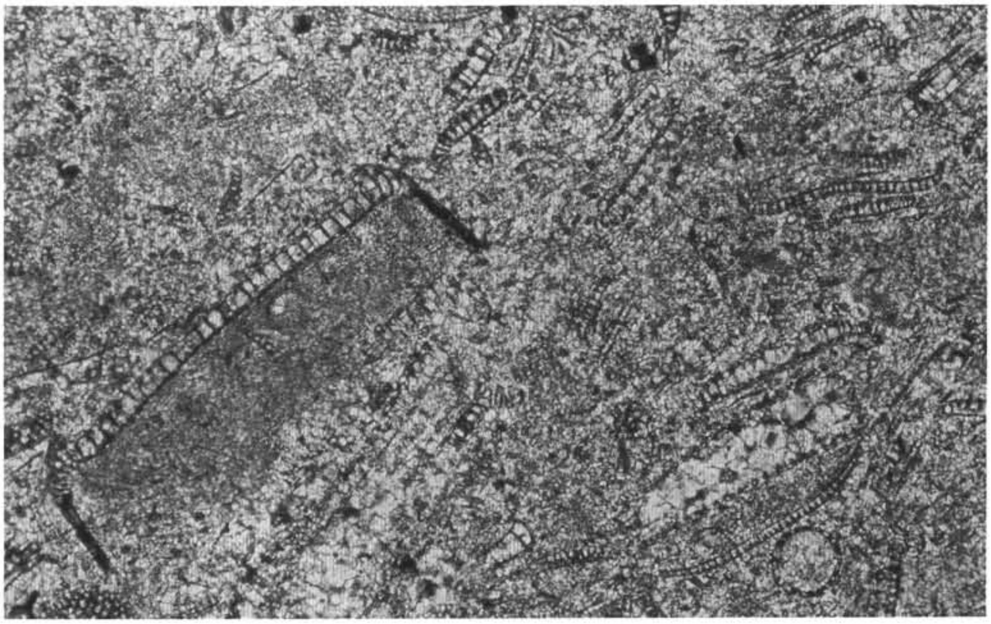

Figure 10. Rhodochrosite-rock dropstone (Sample 145-881C-36X-1, 0–15 cm, pebble 015: washed-in gravel). Isotropic hyaline shards and sparse feldspar fragments are dispersed in the abundant microcrystalline rhodochrosite. Field width is 2 mm.

Table 3. Petrographic clast-type percentages (59 clasts), Site 887.

	Petrographic group	Site 887 (% total clasts)
1	Arkosic or lithofeldspathic sandstones; infracrustal and mixed supracrustal provenance.	29.6
2	Foliated low-grade metasediments; sandstones, phyllites, semischists.	31.4
3	Coarse-grained nonfoliated granulites, hornfelses.	12.9
4	Plutonic intrusives; predominantly granitic, some basic varieties.	16.6
5	Basaltic volcanic rocks.	3.7
6	Quartzose sandstones; fine grained and well sorted, with ferruginous cements.	5.5

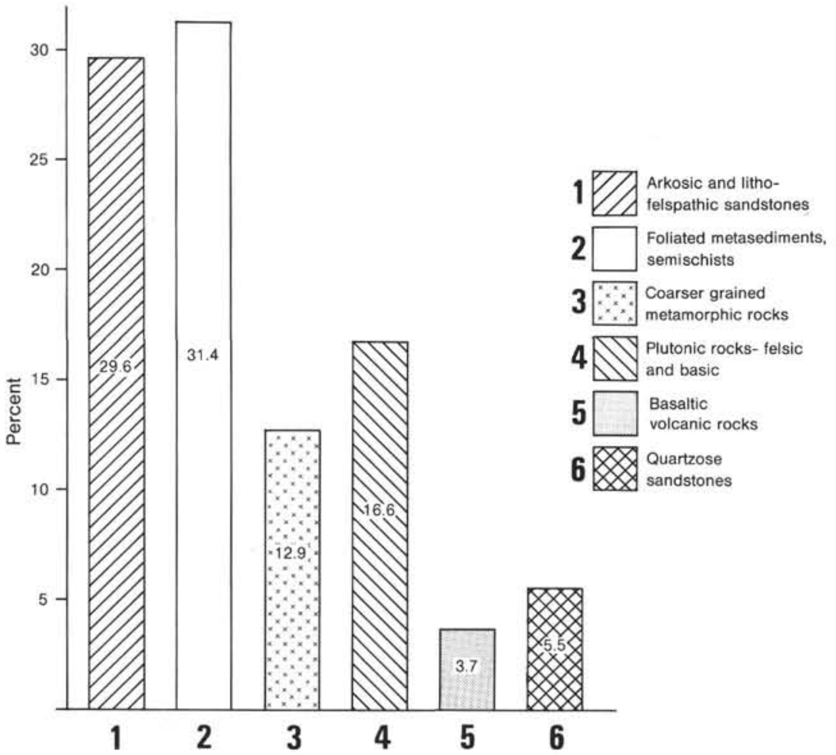

Figure 11. Petrographic clast-type percentages (59 clasts), Site 887.

(Shipboard Scientific Party, 1993b), which is washed-in material obtained from the base of the core (Core 145-887A-30X). Each of these clasts was categorized into one of six broad petrographic groups (Table 3 and Fig. 11).

Discussion

Comparison with the Northwest Pacific dropstones shows that the Site 887 clasts lack both the large and varied volcanic arc(s) and associated volcaniclastic contribution. There is also a complete absence of chert at Site 887. Furthermore, few of the Site 887 sandstones display abundant primary (i.e., depositional) matrices such as are so common in the Northwest Pacific volcaniclastic clasts (e.g., Fig. 4). The much greater abundance of foliated low-grade metamorphics at Site 887 in comparison to the Northwest Pacific sites is noteworthy, as is the relatively high (16.6%) plutonic contribution.

It is difficult to specify precisely the provenance of the Site 887 clasts. It is logical to compare them with clasts in the nearby and in part (at least) contemporaneous glaciomarine Yakataga Formation exposed along the northern reach of the Gulf of Alaska (Eyles and Lagoe, 1990; Eyles et al., 1991). Eyles and Lagoe listed dropstone clasts of "sandstone, siltstones, granites, and mafic extrusive and intrusive igneous rocks all derived from source terrains in the Chugach and St. Elias mountains." These clasts appear to be lithologically similar to the Site 887 clasts. We note also similarities between some of the Site 887 supracrustal derived sandstones and the volcaniclastic sandstones of the Jurassic–Cretaceous Seymour Canal Formation of the Gravina Belt of southeastern Alaska, which lies to the east of the Chugach Terrain, as recently described in detail by Cohen and Lundberg (1993). For these reasons, we assume that the Site 887 dropstones were derived from southeastern Alaska.

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