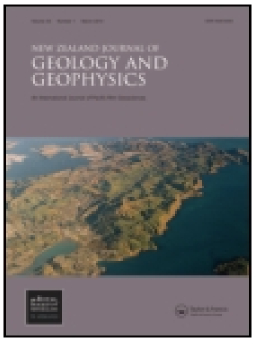

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New Zealand Journal of Geology and Geophysics

ISSN: 0028-8306 (Print) 1175-8791 (Online) Journal homepage: http://www.tandfonline.com/loi/tnzg20

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New Zealand Journal of Geology & Geophysics, 2005, Vol. 48: 649–660
0028–8306/05/4804–0649

Petrography of quartz grains in beach and dune sands of Northland, North Island, New Zealand

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Abstract Petrographic and scanning electron microscopy (SEM) analyses of quartz grains from beach and dune sands were carried out in the western and eastern Northland coasts, New Zealand, to examine variations in durability and surface texture, which are controlled by mechanical and chemical processes, in profiles across beach and dune environments. This was done through point counts of quartz grain properties based on extinction angle and crystallinity. Variations in surface texture were assessed through SEM observations of mechanical features (conchoidal fractures, smooth surfaces, groove forms) and chemical features (solution pits, etching, silica deposits). Mechanically produced grooves are associated with beach sands affected by the high energy of the surf zone. Both mechanical and chemical processes occur in the eastern dune sands. They are associated with the greater abundance of angular grains in the eastern dune sands than the western dune sands. In addition, conchoidal fractures produced by the collision of grains in aeolian environments and linear and curved grooves produced by quartz grains from the beach support the mechanical processes taking place in the dunes. Solution pits, etching, and the presence of diatoms in the quartz grains are associated with pedogenesis and high silica precipitation in the eastern beach and dune sands. The durability of coarse-grained polycrystalline quartz relative to fine-grained polycrystalline quartz suggests that chemical abrasion exerts control over the distribution of quartz types in the dune sands.

Keywords polycrystalline quartz; monocrystalline quartz; quartz; beach and dune sands; SEM; New Zealand

G05001; Online publication date 10 October 2005
Received 12 January 2005; accepted 22 July 2005

INTRODUCTION

The abundance of quartz in igneous, sedimentary, and metamorphic rocks makes it the most common detrital constituent of terrigenous sediments (Pettijohn et al. 1972). The shapes of detrital quartz grains are susceptible to change by mechanical and chemical processes during cycles of erosion, transportation, and deposition (Crook 1968; Moss 1972; Mazzullo et al. 1986; Pye & Mazzullo 1994). Due to their many varieties, quartz grains have also been used for durability and provenance studies (Blatt & Christie 1963; Basu et al. 1975; Harrell & Blatt 1978; Kwon & Boggs Jr 2002). Some studies have focused on scanning electron microscope (SEM) analysis to interpret the mechanical and chemical processes that characterise the shape and surface features of quartz grains (Mazzullo et al. 1986; Pye & Mazzullo 1994; Moral Cardona et al. 1997; Al-Hurban & Gharib 2004). However, these studies have not considered the mechanical and chemical processes that modify quartz grains from modern beach and dune environments, as well as their durability in these environments. Durability is defined as the percent of the initial amount of granule-size sediment remaining after tumbling (Harrell & Blatt 1978).

This paper examines quartz grains in transects across beaches and dunes on the eastern and western coasts of the Aupouri Peninsula in Northland, New Zealand. The aims are to: (1) show variations in quartz types and surface texture; (2) relate these variations to mechanical and chemical processes; and (3) establish *in situ* durability of different quartz types. The study demonstrates the relationship between quartz types, durability, and mechanical and chemical processes across beach and dune profiles by means of point-counting methods and SEM analysis. The mineralogy and properties of Northland's coastal sand deposits are of economic importance since 75 000 t of quartz sand with 90–96% quartz is dredged annually from the northern east coast of the Aupouri Peninsula (Schofield 1970; Isaac 1996).

STUDY AREA

The Aupouri Peninsula is a Pleistocene tombolo, which forms the northernmost tip of Northland, New Zealand (Fig. 1). Beach and dune sands on the western side of this peninsula contain 65–75% quartz, whereas those on the eastern side contain 90–94% quartz (Schofield 1970). Based on Schofield's data (1970) on the western coast, the beach and dune sands on the western side of the Aupouri Peninsula are quartzitic (beach Q_{67} F_{18} L_{15}; dune Q_{71} F_{13} L_{16}) (Table 1), and the mean grain-size is 2.45–2.75 ϕ (fine sand).

Prevailing winds are from the west and drive the strong north-flowing currents longshore littoral on the western side of the peninsula. The eastern side of the peninsula is subjected to a northwestward longshore current that could be the result of local eddies caused by promontories along the irregular coast (Schofield 1970). There is also evidence

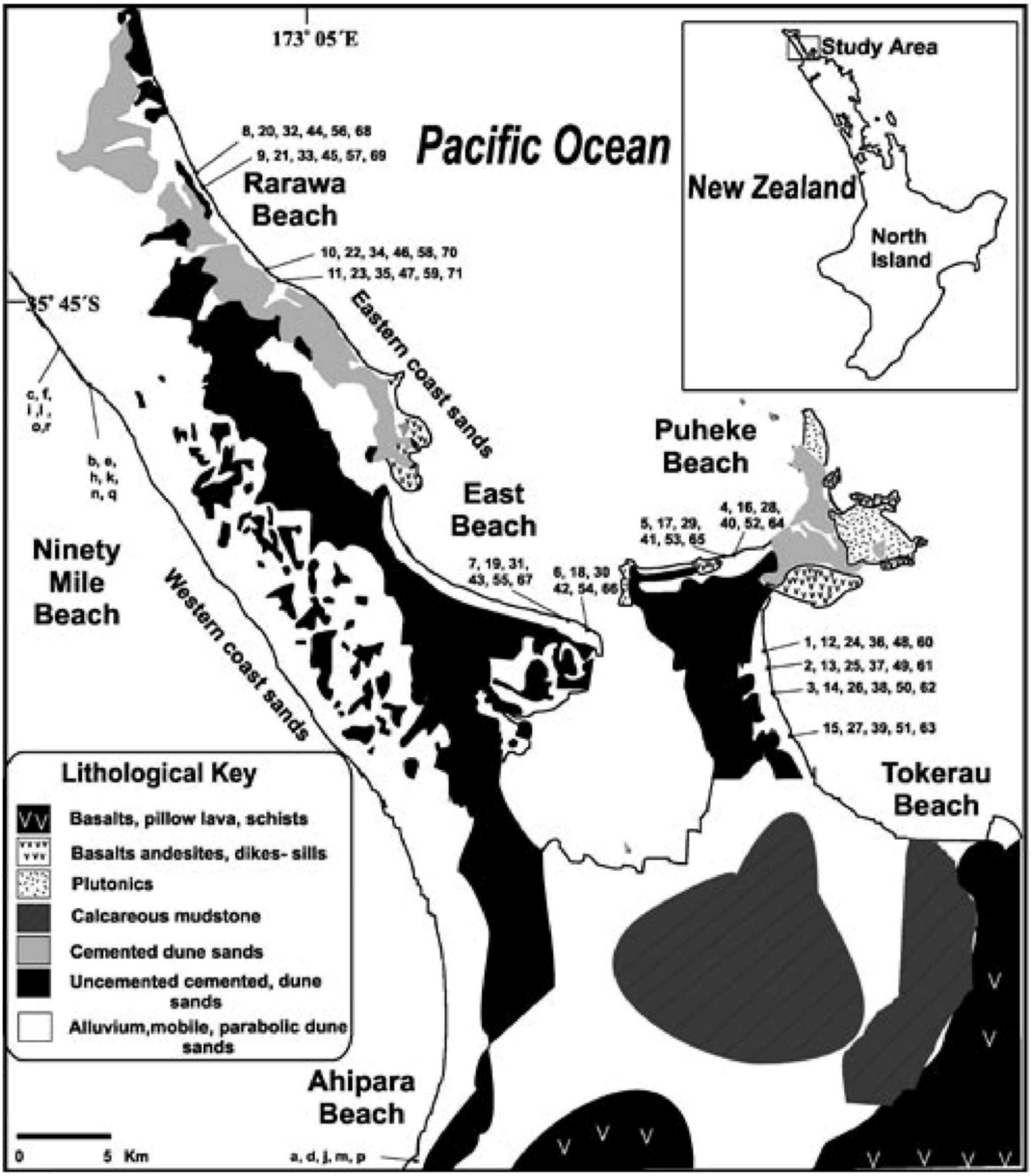


Fig. 1 Sampling sites and geology of the study area (after Isaac 1996).

of a southeastward offshore surface current (Schofield 1970). The eastern coast is characterised by small amounts of prograded deposits when compared with the larger amounts on the western coast (Fig. 1). Progradation is related to beach sand deposits during low sea level stands where sands were supplied from the seafloor (Schofield 1970). Currently, lack of sedimentary supply and less wave energy along the eastern coast as compared to the western coast preserves the sand features in the western coast associated with the progradation mechanisms like the Aupori Tombolo (Schofield 1970).

The contrast in quartz content of the sands between the western and eastern coasts of the peninsula is noteworthy. Schofield (1970) suggested that sands of the Aupouri Peninsula are derived from the western coast of New Zealand south of Ahipara Beach (Fig. 1). The sands were transported northwards by strong longshore currents to form the tombolo during the Pleistocene. Quartz enrichment of the sands on the eastern coast probably occurred through podzolisation under the extensive kauri forests, which have existed for at least 50 000 yr (Isaac 1996). Erosion of these soils during Holocene sea-level rise would have provided the source for the enriched quartzose content of the beach sands. The Mount Camel Terrane underlies most of the Aupouri Peninsula and is composed of Early Cretaceous basaltic and andesitic rocks (Rangiawhia Volcanics), plutons (Rangiputa Granophyre), and sedimentary and metamorphic units (Tokerau Facies) (Isaac et al. 1994; Isaac 1996).

METHODS AND EQUIPMENT

Petrography of quartz grains

A total of 89 beach (n = 44) and dune (n = 45) sands were sampled from the western and eastern coasts of Northland, New Zealand (Fig. 1). Sand samples from the eastern coast were taken at Tokerau, Puheke, East, and Rarawa Beaches and those from the western coast were sampled at Ahipara and Ninety Mile Beaches (Fig. 1). Surface sediments were sampled along the beach and dune profiles. Only modern sand samples were taken from the inshore, foreshore, and backshore of the beach and the stoss, crest, and lee face of the dune. Samples from the podzols dune units were not collected because only relationships for coastal beach and dune sands with mechanical and chemical processes were established.

The grain-size values for the western coast dune sands were taken from Schofield's (1970) grain-size data for several localities (N9/101, N9/102, N9/103, N9/104, N4/158, N41/158/, N4/159) close to the sites sampled for this study (e.g., Ahipara Beach, Ninety Mile Beach). For the eastern coastal sands, dry sieving was carried out at 0.5 ϕ intervals and grain-size parameters (Mz, mean grain-size; σ = sorting) were determined according to Folk (1980). For the western and eastern sands, a split of the whole sample was impregnated and thin-sectioned for quartz counting (Tables 2, 3, 4). In addition, the traditional Indiana point counting method (i.e., 100 grains per slide) was carried out for the western sands to compare their composition with that of the eastern sands, based on the proportions of quartz, feldspar, lithics, and accessories (mica, heavy minerals) (Table 1). Grid distance was greater than the maximum grain size to avoid observations of the same grain (Van der Plas & Tobi 1965; Galehouse 1971). One hundred quartz grains were counted for beach and dune sands following the traditional quartz classifications (Basu et al. 1975; Blatt et al. 1980).

To observe changes in durability and abrasion of quartz types between beach and dune sands, two variables were expressed as ratios: Po/Mo (polycrystalline quartz/monocrystalline quartz) and Ro/An (monocrystalline rounded-subrounded quartz with undulose to straight extinction/monocrystalline angular to subangular quartz with undulose to straight extinction) (Fig. 2; Tables 2, 3, 4). Both ratios aim to assess the durability and abrasion of different composite quartz types deposited in marine and aeolian environments (Beal & Shepard 1956; Harrell & Blatt 1978; Sagga 1993). To quantify durability, quartz grains were counted as monocrystalline: (1) Sr-r, subrounded to rounded with straight extinction; (2) Sa-a, subangular to angular with straight extinction; (3) Sr-r*, subrounded to rounded with undulose extinction; (4) Sa-a*, subangular to angular with undulose extinction (Basu et al. 1975; Pye & Mazzullo 1994); and (5) I, inclusions (biotite, zircon) and/or rutile needles of plutonic/metamorphic origin (Di Giulio et al. 1999). Polycrystalline (>2 crystals) quartz grains were counted as: (1) Cr, grains with crenulated boundaries of metamorphic origin (Folk 1980); (2) Cs, grains with straight contacts (c. 120°) (Voll 1960); and (3) Ch, sedimentary chert (including fine-grained and silty chert). All of these quartz types were included in the experiments on durability of quartz grains carried out by Harrell & Blatt (1978).

Table 1 Point count data for the western coast beach and dune sands.

	Grid reference	Mo	Po	Ft	Lv	Ls	Lm	Lp	Acc
Beach									
A	Kaitaia 524670	65	1	9	9	0	2	9	5
B	Kaitaia 501723	54	5	27	1	4	0	8	1
C	Kaitaia 499729	57	2	33	3	1	1	2	1
D	Kaitaia 524670	64	0	6	5	4	3	12	6
E	Kaitaia 501723	60	0	24	6	2	0	4	4
F	Kaitaia 499729	78	3	12	3	2	0	2	0
G	Kaitaia 524670	56	4	14	9	2	1	8	6
H	Kaitaia 501723	62	0	19	2	8	0	8	1
I	Kaitaia 499729	65	7	15	3	8	0	2	0
Av.		62.33	2.44	17.67	4.56	3.44	0.78	6.11	2.67
SD		7.12	2.51	8.86	2.92	2.88	1.09	3.69	2.55
Dune									
J	Kaitaia 524670	57	2	9	7	5	0	11	9
K	Kaitaia 501723	63	1	17	3	4	0	12	0
L	Kaitaia 499729	73	3	13	4	2	0	5	0
M	Kaitaia 524670	64	3	7	1	8	1	11	5
N	Kaitaia 501723	64	2	23	1	2	0	5	3
O	Kaitaia 499729	65	9	9	6	4	1	4	2
P	Kaitaia 524670	56	3	12	1	6	1	8	13
Q	Kaitaia 501723	60	6	21	3	3	1	6	0
R	Kaitaia 499729	68	12	6	1	3	0	9	1
Av.		63.33	4.56	13.00	3.00	4.11	0.44	7.89	3.67
SD		5.29	3.71	6.10	2.29	1.96	0.53	3.02	4.58

Mo, monocrystalline quartz; Po, polycrystalline quartz; Ft, total feldspar; Lv, volcanic lithics; Ls, sedimentary lithics; Lm, metamorphic lithics; LP, plutonic lithics; Acc, accessories (calcite, mica, magnetite, heavies). SD, standard deviation.

Table 2 Quartz-type point counts and ratios of beach and dune sand samples from the western coast.

Subenvironment	Sample	Grid reference	Sr-r	Sa-a	Sr-r*	Sa-a*	I	Cr	Cs	Ch	Po/Mo ratio	Ro/An ratio
Inshore	A	Kaitaia 524670	14	37	19	14	2	5	9	0	0.16	0.65
Inshore	B	Kaitaia 501723	12	54	11	11	1	2	8	1	0.12	0.35
Inshore	C	Kaitaia 499729	18	51	6	12	5	3	5	0	0.09	0.38
	Av.		14.67	47.33	12	12.33	2.67	3.33	7.33	0.33	0.12	0.45
	SD		3.06	9.07	6.56	1.53	2.08	1.53	2.08	0.58	0.04	0.16
Foreshore	D	Kaitaia 524670	17	56	3	16	1	4	3	0	0.08	0.28
Foreshore	E	Kaitaia 501723	18	37	10	18	1	1	13	2	0.19	0.51
Foreshore	F	Kaitaia 499729	23	58	2	7	3	1	6	0	0.08	0.38
	Av.		19.33	50.33	5	13.67	1.67	2.00	7.33	0.67	0.11	0.38
	SD		3.21	11.59	4.36	5.86	1.15	1.73	5.13	1.15	0.07	0.12
Backshore	G	Kaitaia 524670	25	54	0	8	4	1	8	0	0.10	0.40
Backshore	H	Kaitaia 501723	25	58	6	3	3	0	5	0	0.05	0.51
Backshore	I	Kaitaia 499729	24	51	6	4	6	4	4	1	0.10	0.55
	Av.		24.67	54.33	4.00	5.00	4.33	1.67	5.67	0.33	0.08	0.48
	SD		0.58	3.51	3.46	2.65	1.53	2.08	2.08	0.58	0.03	0.07
Stoss	J	Kaitaia 524670	38	43	6	5	2	2	4	0	0.06	0.92
Stoss	K	Kaitaia 501723	33	45	5	6	6	2	3	0	0.05	0.75
Stoss	L	Kaitaia 499729	40	43	3	1	5	0	8	0	0.09	0.98
	Av.		37.00	43.67	4.67	4.00	4.33	1.33	5.00	0.00	0.07	0.87
	SD		3.61	1.15	1.53	2.65	2.08	1.15	2.65	0.00	0.02	0.12
Crest	M	Kaitaia 524670	51	34	4	2	5	0	4	0	0.04	1.53
Crest	N	Kaitaia 501723	42	45	0	5	2	0	6	0	0.06	0.84
Crest	O	Kaitaia 499729	42	44	3	0	2	4	5	0	0.10	1.02
	Av.		45.00	41.00	2.33	2.33	3.00	1.33	5.00	0.00	0.07	1.09
	SD		5.20	6.08	2.08	2.52	1.73	2.31	1.00	0.00	0.03	0.36
Lee face	P	Kaitaia 524670	32	53	3	5	1	0	6	0	0.06	0.60
Lee face	Q	Kaitaia 501723	34	46	2	5	3	3	6	1	0.11	0.71
Lee face	R	Kaitaia 499729	49	33	4	3	4	1	6	0	0.08	1.47
	Av.		38.33	44.00	3.00	4.33	2.67	1.33	6.00	0.33	0.08	0.86
	SD		9.29	10.15	1.00	1.15	1.53	1.53	0.00	0.58	0.02	0.47

Sr-r = subrounded to rounded monocrystalline quartz with straight extinction; Sa-a = subangular to angular monocrystalline quartz with straight extinction; Sr-r* = subrounded to rounded monocrystalline quartz with undulose extinction; Sa-a* = subangular to angular monocrystalline quartz with undulose extinction; I = monocrystalline quartz with rutile-zircon-biotite inclusions or needles; Cr = polycrystalline quartz with crenulated boundaries; Cs = polycrystalline quartz with straight boundaries (c. 120°), overgrowth crystals (>3 crystals per grain); Ch = chert (including fine-grained and silty chert); Po (polycrystalline quartz) = Cr + Cs + Ch; Mo (monocrystalline quartz) = Sr-r + Sa-a + Sr-r* + Sa-a * + I ; Ro (rounded quartz) = Sr-r + Sr-r* ; An (angular quartz) = Sa-a + Sa-a*.

Table 3 Quartz-type point counts and ratios of beach sand samples from the eastern coast.

Subenvironment	Sample	Grid reference	Mz	σ	Sr-r	Sa-a	Sr-r*	Sa-a*	I	Cr	Cs	Ch	Po/Mo ratio	Ro/An ratio
Inshore	1	Kaitaia 545702	2.43	0.50	9	6	18	30	1	6	17	13	0.56	0.75
Inshore	2	Kaitaia 545703	2.50	0.65	12	7	25	21	2	13	9	11	0.49	1.32
Inshore	3	Kaitaia 546704	2.64	0.41	15	12	24	28	5	7	3	6	0.19	0.98
Inshore	4	Kaitaia 542705	1.99	0.46	13	27	7	34	3	4	5	7	0.19	0.33
Inshore	5	Kaitaia 543705	2.28	0.64	21	24	12	32	5	5	0	1	0.06	0.59
Inshore	6	Kaitaia 536701	2.12	0.29	7	26	9	32	3	9	9	5	0.30	0.28
Inshore	7	Kaitaia 535702	2.22	0.27	8	31	3	32	5	13	7	1	0.27	0.17
Inshore	8	Kaitaia 515725	1.71	0.27	36	28	9	10	1	8	2	6	0.19	1.18
Inshore	9	Kaitaia 515724	1.74	0.26	25	18	13	29	2	7	5	1	0.15	0.81
Inshore	10	Kaitaia 519720	2.20	0.29	15	28	4	35	3	9	4	2	0.18	0.30
Inshore	11	Kaitaia 518721	1.63	0.60	5	25	4	24	1	23	8	10	0.69	0.18
	Av.		2.13	0.42	15.09	21.09	11.64	27.91	2.82	9.45	6.27	5.73	0.30	0.63
	SD		0.33	0.16	9.16	8.92	7.75	7.26	1.60	5.34	4.58	4.27	0.20	0.41
Foreshore	12	Kaitaia 545702	2.66	0.42	13	12	17	20	11	11	3	18	0.44	0.94
Foreshore	13	Kaitaia 545703	2.71	0.51	14	11	35	16	5	3	2	12	0.21	1.81
Foreshore	14	Kaitaia 545703	2.87	0.30	17	14	16	27	13	7	6	9	0.25	0.80
Foreshore	15	Kaitaia 545705	2.65	0.43	14	21	26	13	14	10	4	7	0.24	1.18
Foreshore	16	Kaitaia 542705	2.52	0.46	14	30	6	26	11	10	1	2	0.15	0.36
Foreshore	17	Kaitaia 543705	2.31	0.62	9	32	6	28	6	4	2	15	0.26	0.25
Foreshore	18	Kaitaia 536701	2.11	0.29	8	32	3	28	12	10	2	2	0.17	0.18
Foreshore	19	Kaitaia 535702	1.76	0.47	9	25	7	42	6	6	0	1	0.08	0.24
Foreshore	20	Kaitaia 515725	2.21	0.29	20	31	10	18	7	6	1	5	0.14	0.61
Foreshore	21	Kaitaia 515724	1.60	0.28	16	23	14	21	9	7	2	7	0.19	0.68
Foreshore	22	Kaitaia 519720	2.54	0.44	4	23	8	39	14	11	3	1	0.17	0.19
Foreshore	23	Kaitaia 518721	2.27	0.61	1	29	4	39	14	7	7	2	0.18	0.07
	Av.		2.35	0.43	11.58	23.58	12.67	26.42	10.17	7.67	2.75	6.75	0.21	0.61
	SD		0.39	0.12	5.52	7.75	9.96	9.51	3.43	2.71	2.05	5.75	0.09	0.51

(continued)

Table 3 *(continued)*

Subenvironment	Sample	Grid reference	Mz	σ	Sr-r	Sa-a	Sr-r*	Sa-a*	I	Cr	Cs	Ch	Po/Mo ratio	Ro/An ratio
Backshore	24	Kaitaia 545702	2.22	0.30	30	13	14	20	4	10	2	5	0.21	1.33
Backshore	25	Kaitaia 545703	2.47	0.49	25	20	18	18	1	10	1	3	0.17	1.13
Backshore	26	Kaitaia 545703	2.12	0.11	21	23	11	20	7	11	4	3	0.22	0.74
Backshore	27	Kaitaia 545705	2.17	0.75	13	25	9	20	3	13	3	9	0.36	0.49
Backshore	28	Kaitaia 542705	2.27	0.63	18	31	12	27	2	9	2	0	0.12	0.52
Backshore	29	Kaitaia 543705	1.73	0.28	27	27	9	17	3	8	1	2	0.13	0.82
Backshore	30	Kaitaia 536701	2.15	0.30	5	37	4	32	6	8	3	5	0.19	0.13
Backshore	31	Kaitaia 535702	2.02	0.43	6	20	4	46	2	7	1	7	0.19	0.15
Backshore	32	Kaitaia 515725	2.26	0.56	22	20	17	25	4	8	3	2	0.15	0.87
Backshore	33	Kaitaia 515724	2.05	0.45	8	30	7	33	6	5	1	3	0.11	0.24
Backshore	34	Kaitaia 519720	2.26	0.58	5	19	2	52	4	5	1	6	0.15	0.10
Backshore	35	Kaitaia 518721	2.28	0.59	8	18	4	46	4	9	1	5	0.19	0.19
	Av.		2.17	0.46	15.67	23.58	9.25	29.67	3.83	8.58	1.92	4.17	0.18	0.56
	SD		0.18	0.18	9.25	6.09	5.31	12.26	1.80	2.31	1.08	2.48	0.07	0.42

Mz, Mean grain-size (ϕ); σ, sorting; see Table 2 for abbreviations.

Table 4 Quartz-type point counts and ratios of dune sand samples from the eastern coast.

Subenvironment	Sample	Grid reference	Mz	σ	Sr-r	Sa-a	Sr-r*	Sa-a*	I	Cr	Cs	Ch	Po/Mo ratio	Ro/An ratio
Stoss	36	Kaitaia 545702	2.68	0.40	6	17	5	57	2	6	4	3	0.15	0.15
Stoss	37	Kaitaia 545703	2.78	0.38	11	25	14	36	4	2	4	4	0.11	0.41
Stoss	38	Kaitaia 545703	2.53	0.48	8	18	3	50	1	7	6	7	0.25	0.16
Stoss	39	Kaitaia 545705	2.49	0.59	6	19	2	49	3	4	5	12	0.27	0.12
Stoss	40	Kaitaia 542705	2.04	0.47	10	14	10	42	4	9	7	4	0.25	0.36
Stoss	41	Kaitaia 543705	1.66	0.29	12	17	10	47	7	4	3	0	0.08	0.34
Stoss	42	Kaitaia 536701	2.10	0.30	6	14	13	49	1	7	7	3	0.20	0.30
Stoss	43	Kaitaia 535702	1.62	0.30	15	15	6	48	1	8	4	3	0.18	0.33
Stoss	44	Kaitaia 515725	2.22	0.56	30	24	8	31	1	2	2	2	0.06	0.69
Stoss	45	Kaitaia 515724	2.23	0.28	17	30	7	36	2	6	1	1	0.09	0.36
Stoss	46	Kaitaia 519720	2.12	0.62	10	22	3	41	2	10	8	4	0.28	0.21
Stoss	47	Kaitaia 518721	2.29	0.60	3	24	3	44	2	10	9	5	0.32	0.09
	Av.		2.23	0.44	11.17	19.92	7.00	44.17	2.50	6.25	5.00	4.00	0.19	0.29
	SD		0.36	0.13	7.16	5.05	4.07	7.32	1.78	2.80	2.45	3.10	0.09	0.17
Crest	48	Kaitaia 545702	3.01	0.59	7	18	5	47	1	7	1	14	0.28	0.18
Crest	49	Kaitaia 545703	2.73	0.34	10	33	2	39	7	2	6	1	0.10	0.17
Crest	50	Kaitaia 545703	2.46	0.46	12	10	13	49	2	3	4	7	0.16	0.42
Crest	51	Kaitaia 545705	2.36	0.64	8	19	3	48	2	6	9	5	0.25	0.16
Crest	52	Kaitaia 542705	2.04	0.47	13	18	5	52	2	1	8	1	0.11	0.26
Crest	53	Kaitaia 543705	1.60	0.30	17	27	6	33	3	5	6	3	0.16	0.38
Crest	54	Kaitaia 536701	2.08	0.29	15	21	6	41	2	7	2	6	0.18	0.34
Crest	55	Kaitaia 535702	2.04	0.44	8	11	8	56	1	8	7	1	0.19	0.24
Crest	56	Kaitaia 515725	2.27	0.27	14	34	6	36	0	7	2	1	0.11	0.29
Crest	57	Kaitaia 515724	2.04	0.45	19	25	6	33	2	10	2	3	0.18	0.43
Crest	58	Kaitaia 519720	2.60	0.72	11	31	3	34	3	7	7	4	0.22	0.22
Crest	59	Kaitaia 518721	2.28	0.61	7	26	5	54	0	4	3	1	0.09	0.15
	Av.		2.29	0.47	11.75	22.75	5.67	43.50	2.08	5.58	4.75	3.92	0.17	0.27
	SD		0.37	0.15	3.98	7.96	2.84	8.50	1.83	2.64	2.73	3.82	0.06	0.10
Lee face	60	Kaitaia 545702	2.58	0.58	7	23	9	45	2	3	5	6	0.16	0.24
Lee face	61	Kaitaia 545703	2.67	0.43	9	18	14	36	1	4	12	6	0.28	0.43
Lee face	61	Kaitaia 545703	2.51	0.43	7	20	9	52	0	4	2	6	0.14	0.22
Lee face	63	Kaitaia 545705	2.72	0.43	10	16	7	43	4	7	6	7	0.25	0.29
Lee face	64	Kaitaia 542705	1.88	0.48	16	21	15	36	3	4	1	4	0.10	0.54
Lee face	65	Kaitaia 543705	1.62	0.30	16	17	12	39	0	6	6	4	0.19	0.50
Lee face	66	Kaitaia 536701	2.15	0.28	10	24	11	39	0	11	4	1	0.19	0.33
Lee face	67	Kaitaia 535702	1.89	0.44	3	19	8	44	3	9	9	5	0.30	0.17
Lee face	68	Kaitaia 515725	2.41	0.41	26	24	10	33	1	3	3	0	0.06	0.63
Lee face	69	Kaitaia 515724	1.99	0.45	22	18	10	36	1	8	5	0	0.15	0.59
Lee face	70	Kaitaia 519720	2.09	0.71	10	30	10	42	2	2	1	3	0.06	0.28
Lee face	71	Kaitaia 518721	2.31	0.29	10	28	7	45	2	5	3	0	0.09	0.23
	Av.		2.23	0.44	12.17	21.50	10.17	40.83	1.58	5.50	4.75	3.50	0.16	0.37
	SD		0.35	0.12	6.63	4.40	2.52	5.34	1.31	2.75	3.25	2.65	0.08	0.16

See Table 2 for abbreviations.

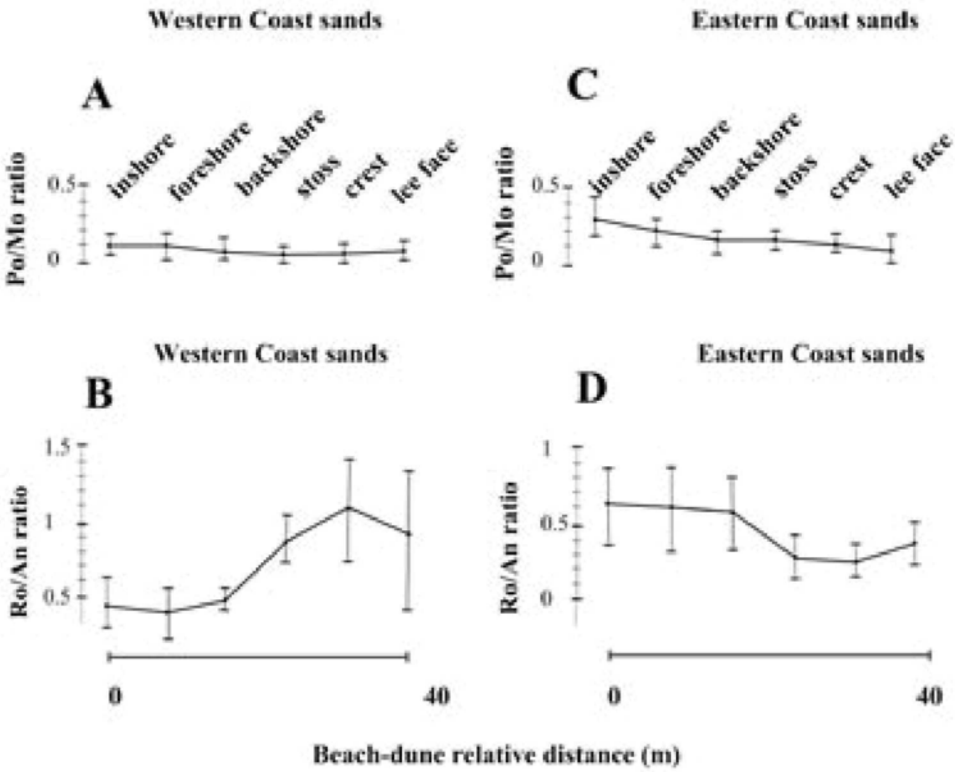


Fig. 2 Cross-shore trends for the average of: (**A**) Po/Mo ratio, western coast sands; (**B**) Ro/An ratio, western coast sands; (**C**) Po/Mo ratio, eastern coast sands; and (**D**) Ro/An ratio eastern coast sands. Bars are confidence levels at 95%.

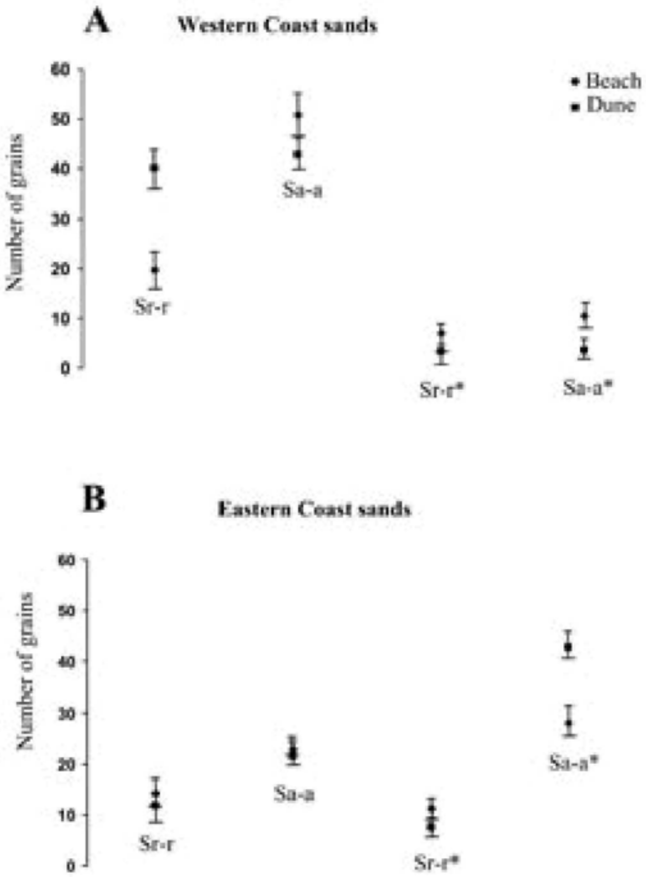


Fig. 3 Average of major quartz constituents (Sr-r, Sa-a, Sr-r*, Sa-a* for (**A**) western coast sands and (**B**) eastern coast sands. Bars are confidence levels at 95%.

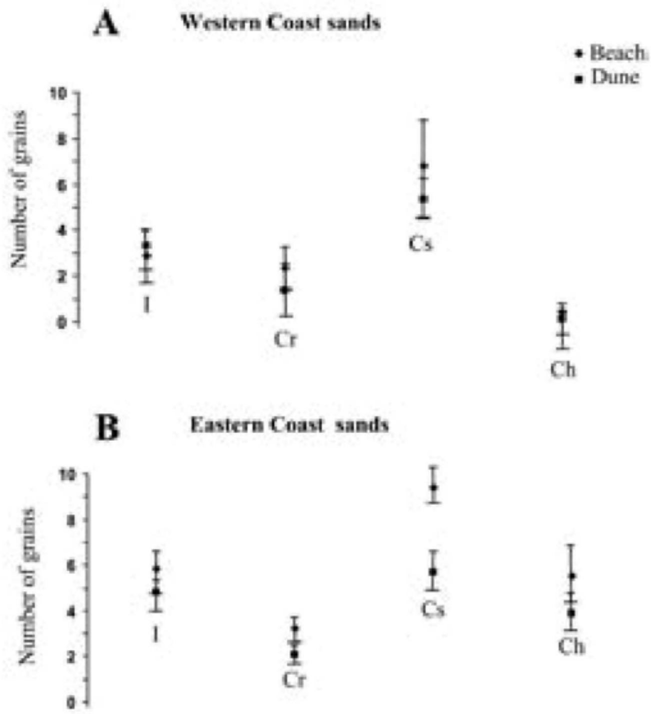


Fig. 4 Average of minor quartz constituents (I, Cr, Cs, Ch) for (**A**) western coast sands and (**B**) eastern coast sands. Bars are confidence levels at 95%.

Major and minor quartz constituents were separated by their abundance or number of grains counted. Overall, major quartz constituents were Sr-r, Sa-a, Sr-r*, and Sa-a*, and minor quartz constituents were I, Cr , Cs, and Ch (Fig. 3, 4; Tables 2, 3, 4).

SEM observations were carried out on 14 selected samples of beach and dune sands (Table 5). Observations were based on mechanical features (conchoidal fractures, smooth surfaces, mechanical V-forms, linear or curved grooves) (Fig. 5A–E) and chemical features (solution pits and etching, silica deposits) displayed in quartz grains (Fig. 5F–H) (Whalley et al. 1987; Pye & Mazzullo 1994; Moral Cardona et al. 1997).

Statistical analysis

Cross-shore durability and abrasion trends and quartz types related to primary rock sources were evaluated by *t*-tests for the beach and dune sand samples ($n = 71$) (Table 6). Ratios of Po/Mo and Ro/An were used to observe significant differences between beach and dune sands, and quartz types were grouped into major and minor components based on their abundance. *t*-tests were used to evaluate the mean differences between the two groups (beach and dune) assuming that the variables were normally distributed and variances are homogeneous (Swan & Sandilands 1995).

RESULTS

Western coast beach and dune sands

The most significant differences in quartz durability were assessed by means of the Po/Mo and Ro/An ratios because polycrystallinity and roundness are the best indicators of this characteristic (Beal & Shepard 1956; Harrell & Blatt 1978; Whalley et al. 1987; Sagga 1993; Pye & Mazzullo 1994) (Table 2). Across the shore there is a slight decrease landwards in the Po/Mo ratio from 0.10 for beach and 0.07 for dune sands (Fig. 2A). The *t*-test showed $t_{observed} = 2.05$ versus $t_{0.05,16} = 1.74$, which indicates that the difference between beach and dune sand is significant (Table 6).

The Ro/An ratio increases landwards (Fig. 2B), and the *t*-test showed a $t_{observed} = -4.65$ versus $t_{0.05,16} = 1.74$ (Table 6), which indicates a significant difference in the Ro/An ratio between the beach and dune sands.

Eastern coast beach and dune sands

Sands on the eastern side are extremely rich in quartz, and the average quartz percentages at Tokerau, East Beach, and Rarawa are 91.05 ± 5.01, 86.23 ± 2.74, and 92.65 ± 2.30%, respectively (Schofield 1970). Eastern beach and dune sands are extremely well sorted and fine grained ($Mz = 2.23$; $\sigma = 0.43$) (Tables 3, 4).

The eastern coast beach and dune sands have a mean Po/Mo ratio of 0.28 and 0.18, respectively. The *t*-test was $t_{observed} = 4.03$ versus $t_{0.05,69} = 1.66$ (Table 6), indicating that differences in the Po/Mo ratio between the beach and dune sands are significant. In addition, there is a slight decrease landwards in the Po/Mo values (Fig. 2C; Tables 3, 4). The eastern coast beach and dune sands have a mean Ro/An ratio of 0.60 and 0.31, respectively. The *t*-test was $t_{observed} = 3.65$ versus $t_{0.05,69} = 1.66$ (Table 6), indicating significant differences in the Ro/An ratio between beach and dune sands.

Table 6 Significant distribution *t*-tests for differences in the mean for the Po/Mo and Ro/An ratios between western sands ($n = 18$; d.f. $= n–2$) and eastern sands ($n = 71$; d.f. $= n–2$).

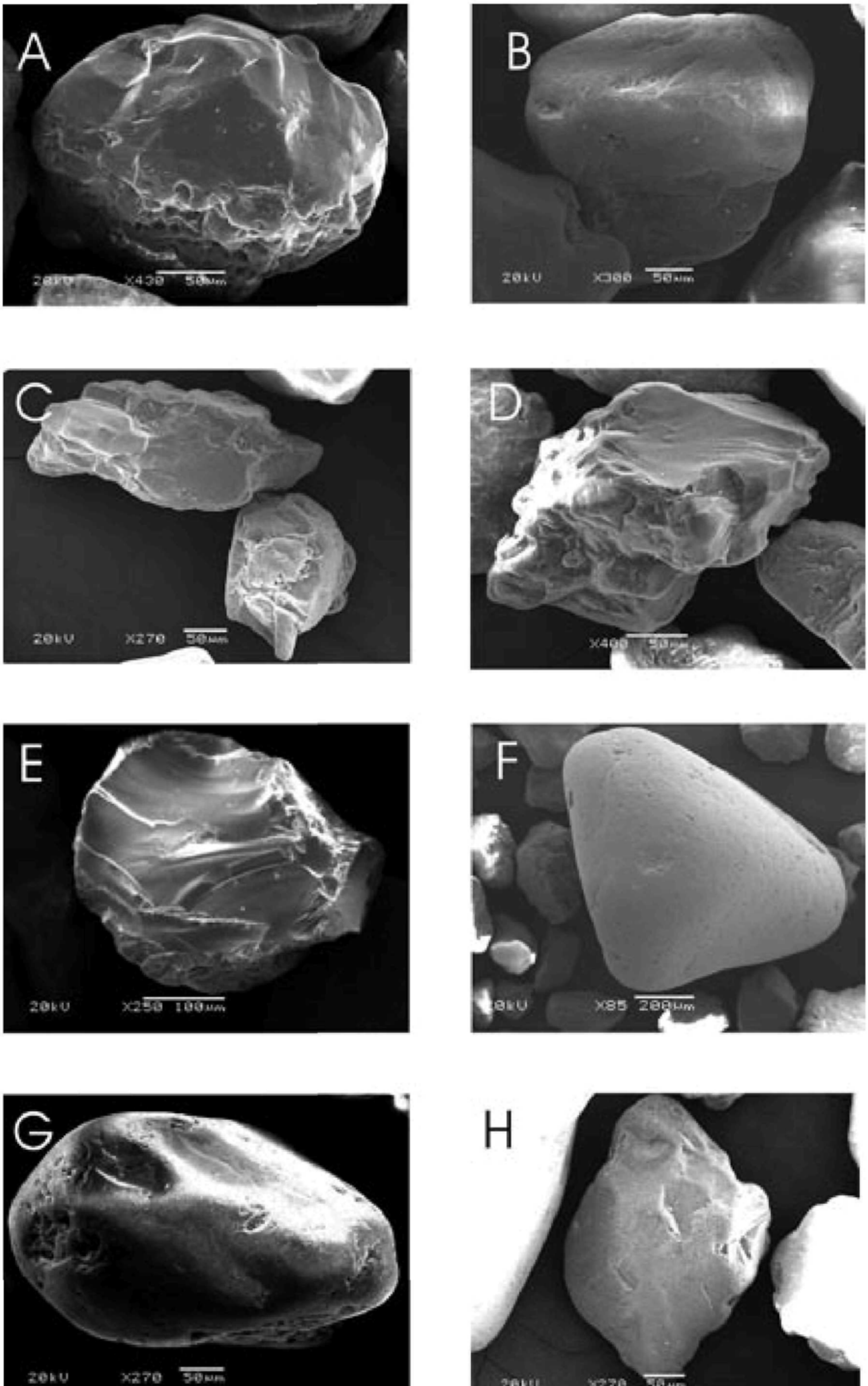
	$t_{observed}$	d.f.	ρ	$t_{critical}$
Western beach and dune sands				
Po/Mo ratio beach versus dune	2.05	16	0.05	1.74
Ro/An ratio beach versus dune	–4.65	16	0.05	1.74
Eastern beach and dune sands				
Po/Mo ratio beach versus dune	4.03	69	0.05	1.66
Ro/An ratio beach versus dune	3.65	69	0.05	1.66

See Table 2 for abbreviations; d.f. = degrees of freedom; $t_{0.05,16} = t_{critical}$ for western coast sands; $t_{0.05,69} = t_{critical}$ for eastern coast sands.

Table 5 Number of quartz grains and factor analysis with surface features of selected samples.

Sample	Grid reference	I	II	III	IV	V	VI	Surface features	Factor 1	Factor 2
A	Kaitaia 524670	7	3	2	1	2	5	Beach		
B	Kaitaia 501723	9	3	1	1	2	4	I	0.05	**0.95**
C	Kaitaia 499729	5	4	1	1	5	4	II	0.15	**–0.91**
M	Kaitaia 524670	6	2	2	1	5	4	III	**0.76**	–0.28
N	Kaitaia 501723	1	5	2	4	5	3	IV	**0.84**	0.33
O	Kaitaia 499729	7	6	1	1	1	4	V	–0.52	–0.01
3	Kaitaia 546704	5	4	1	1	5	4	VI	0.63	0.14
5	Kaitaia 543705	7	3	2	1	1	6	Total variance	0.33	0.32
6	Kaitaia 536701	9	2	1	2	4	2	Dune		
9	Kaitaia 515724	6	6	1	1	4	2	I	**–0.86**	0.43
50	Kaitaia 545703	5	6	1	1	1	6	II	–0.38	**–0.70**
53	Kaitaia 543705	11	2	3	1	1	3	III	–0.17	**0.91**
54	Kaitaia 536701	6	8	1	1	2	2	IV	**0.90**	0.07
57	Kaitaia 515724	3	1	2	3	8	3	V	**0.92**	0.21
								VI	0.02	–0.50
								Total variance	0.43	0.30

I, Conchoidal fractures; II, smooth surfaces; III, mechanical V-forms; IV, linear or curved grooves; V, solution pits and etching; VI, silica deposits. Values in bold typeface are the most significant factor loadings.


A
X430 50μm
B
20kV X300 50μm
C
20kV X270 50μm
D
X400
E
20kV X250 100μm
F
X85 200μm
G
20kV X270 50μm
H
20kV X270 50μm

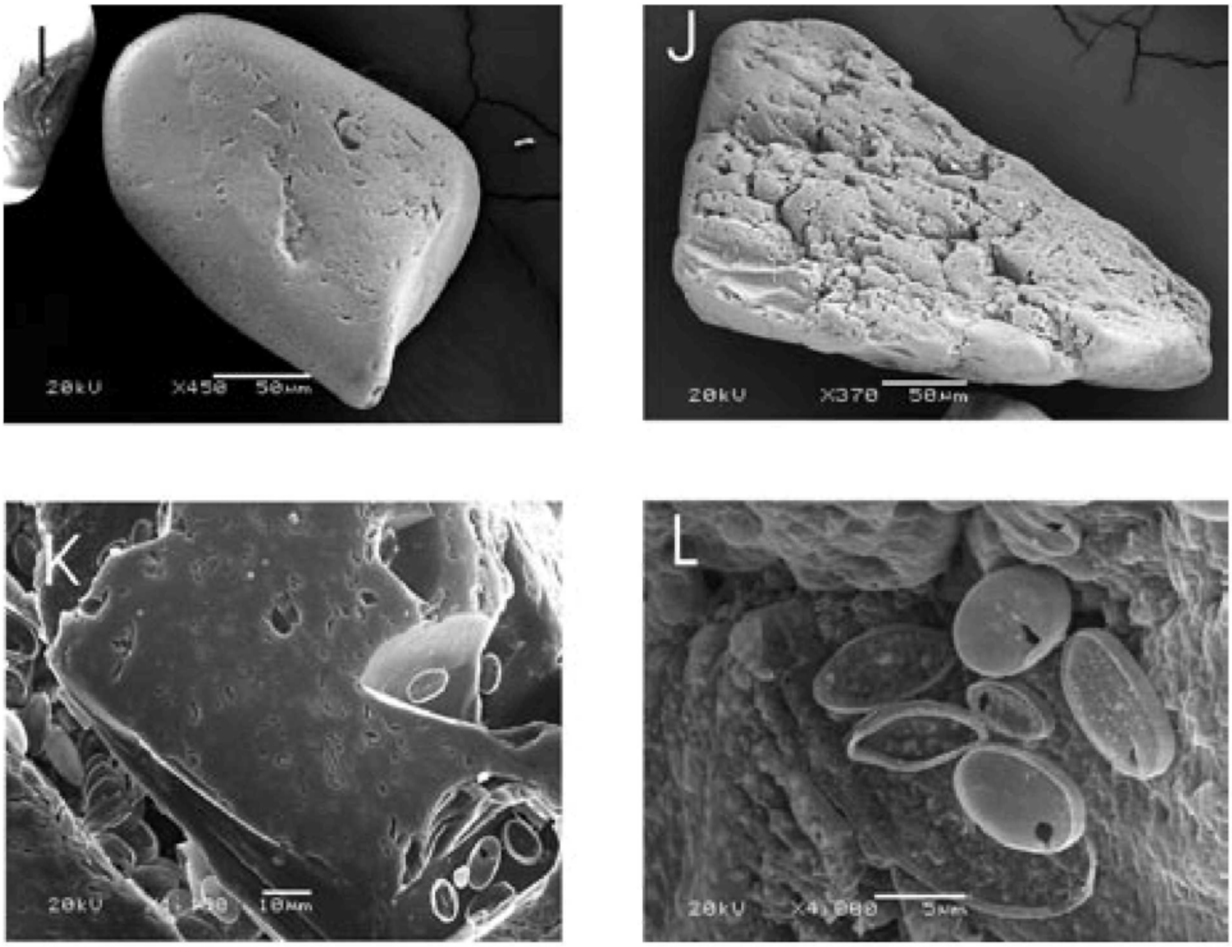


Fig. 5 **A–L** Quartz grain surface features. **A**, Mechanical V-forms (Ahipara Beach, sample A). **B**, Linear or curved grooves (East Beach, sample 6). **C,D** Silica deposits (Ninety Mile Beach, samples B, O). **E**, Conchoidal fractures (Tokerau Beach, sample 50). **F**, Smooth surfaces (Tokerau Beach, sample C). **G,H** Mechanical V-forms (Rarawa Beach, sample 57). **I**, Linear or curved grooves (Rarawa Beach, sample 57). **J**, Solution pits and etching (Rarawa Beach, sample 58). **K,L** Silica deposits with diatom precipitation (Puheke Beach, sample 53).

Durability of major and minor quartz constituents

The western coast sands are high in Sa-a and Cs (Fig. 3A, 4A). Decreasing abundances of quartz types are as follows: Sr-r > Sa-a* ≥ Sr-r*, and I > Cr > Ch (Fig. 3A, 4A).

The eastern coast sands are high in Sa-a* and Cs (Fig. 3B, 4B). Decreasing abundances of quartz types are as follows: Sa-a > Sr-r ≥ Sr-r*, and I ≥ Ch > Cr (Fig. 3B, 4B).

DISCUSSION

Western beach and dune sands

More concentration of polycrystalline quartz in the beach sands than in dune sands may be due to a first-cycle derivation or a short residence time of transportation and deposition in the water (Basu et al. 1975; Harrell & Blatt 1978). However, the landwards decrease in polycrystalline quartz may also be due to breakage of polycrystalline grains into monocrystalline grains caused by chemical instability in the dune. Harrell & Blatt (1978) demonstrated that medium to fine polycrystalline quartz is mechanically more resistant than monocrystalline quartz. In our study, we found that coarse-grained polycrystalline quartz of plutonic origin is more abundant than fine-grained polycrystalline quartz (chert). Therefore, we infer that the breakage of polycrystalline quartz into monocrystalline quartz in the dunes results from chemical weathering and not mechanical abrasion, due to the instability of chert relative to the coarse-grained polycrystalline quartz. This interpretation is also supported by the variation in durability of different quartz types (Harrell & Blatt 1978).

The increase in the Ro/An ratio landwards indicates that quartz grains in the dunes are more rounded than quartz grains in the beach sands, which probably results from grain saltation and suspension and selective sorting in the aeolian environment (Kuenen 1960; Shepard & Young 1961).

The Sa-a and Cs are characteristic of plutonic sources (Basu et al. 1974), and both quartz types have little durability to mechanical abrasion (Blatt & Christie 1963). In all of the sand samples, coarse polycrystalline grains (Cs) are more abundant than fine polycrystalline grains (Ch) (Fig. 3A, 4A). This suggests that sands on the western coast have undergone little mechanical abrasion and that chemical weathering plays an important role in their durability. This is because with decreasing size in polycrystalline quartz, mechanical durability tends to increase whereas chemical durability tends to decrease (Harrell & Blatt 1978). Another possible explanation is the presence of fine polycrystalline aggregates in the sands, which could mask the "durability signal" by means of using different quartz types. Furthermore, in the western sands, no difference was observed between the beach and dune sands in terms of durability of Sa-a and Cs.

Eastern beach and dune sands

As with the western coast beach sands, the slightly higher concentration of polycrystalline quartz versus monocrystalline quartz in the eastern coast beach sands suggests that polycrystalline quartz has not been transported very far. However, in the dune sands, chemical breakdown of polycrystalline quartz may lead to the greater abundance of monocrystalline quartz. Thus, quartz content in the eastern dune sands is probably controlled by chemical breakdown associated with the extensive podsolization and leaching of the dune sands under the kauri forests. The older coastal dunes are inferred to have accumulated during the last interglacial (c. 125 000 yr BP) (Isaac et al. 1994).

Monocrystalline rounded quartz is more abundant in the beach sands than in the dune sands (Fig. 2D). This observation disagrees with the studies by Beal & Shepard (1956) and Shepard & Young (1961), which found that a landward increase in roundness in a beach/dune boundary results from selective sorting by the wind. This "roundness reverse pattern" in monocrystalline quartz between beach and dune sands probably results from chemical etching during podsolization. Furthermore, this suggests that monocrystalline quartz in the eastern dune sands has been subjected to some degree of mechanical breakdown to produce the observed angularity in the grains.

High content of Sa-a* in the eastern sands may result because undulatory quartz has survived mechanical abrasion despite the fact that it is mechanically less stable than non-undulatory quartz (Blatt & Christie 1963). This is also shown in a durability experiment of polycrystalline quartz where 70% of the grains with straight extinction versus 66% of the grains with slightly undulose extinction remained after tumbling (Harrell & Blatt 1978). Furthermore, the dune sands contain higher Sa-a* values than the beach sands, suggesting that the dune preserves less durable quartz types, like Sa-a*, due to little mechanical abrasion compared to the beach.

The eastern coast beach sands have more Cs than their associated dune sands (Fig. 4B). This is because quartz from a granitic source is more chemically durable than fine-grained polycrystalline quartz (Harrell & Blatt 1978). Crenulated fine-grained polycrystalline quartz and chert are less abundant than granitic quartz, which suggests that chemical weathering is the process that controls quartz type in the sands on the eastern side of the Aupouri Peninsula.

Our interpretation of the relationship of durability to the different quartz types, based on the experimental procedures by Harrell & Blatt (1978), is restricted only to the number of quartz grains observed in the thin sections. Therefore, our interpretation is based mainly on our modal analysis and previous literature. We did not take into account the variations of grain shape (removal of the Zingg flatness ratios <0.60) or the grain sizes (gravel sizes –2.0 to –1.0 ϕ) used for the tumbling experiment.

Scanning electron microscopy observation

SEM observations of quartz grains from the western and eastern sands reveal surface textures of conchoidal fractures, solution pits, etching, and silica deposits (Fig. 5A–H; Table 5). A comparison of the relationships among these surface features was done by means of an R-mode factor analysis (Voudouris et al. 1997), which allows selection of the dominant variable. However, interpretations are made in conjunction with the petrologic results.

Beach sands

Linear and curved grooves are mechanical V-forms, which are grouped in Factor 1. This factor accounts for 32.97% of the total variance (Table 5). Mechanical V-forms are probably caused by gouging when one grain strikes another (Krinsley & Donahue 1968). This occurs in high energy environments such as the surf zone of the beach. Linear and curved grooves are found on most littoral grains and are used to infer wave action (Krinsley & Donahue 1969). In the beach sands of the Aupouri Peninsula, surface textures on quartz grains are related mostly to mechanical processes and little to chemical abrasion. The landward decrease in the Po/Mo ratio supports chemical abrasion, which could produce a decrease in fine polycrystalline grains (Po), such as chert. (Fig. 3A,B). However, the landward decrease in the Ro/An ratio for eastern sands supports mechanical abrasion, which takes place in the eastern coast sands but not in the western coast sands. This may be due to the fact that grain size in the eastern coast sands is slightly coarser ($Mz = 2.22–2.25$ ϕ) than in the western coast sands ($Mz = 2.45–2.75$ ϕ). This difference in grain size is probably associated with a wider coastal plain in the western coast as compared to the eastern coast. The eastern coast sands "trap" slightly coarser grains compared to the western coast in small bays and embayments, whereas the wide western coast plains exert a control in the fining of the sands with more dynamic longshore transport. This pattern has been observed also in other coastal areas such as the Baja California Peninsula, Mexico (Carranza-Edwards et al. 1998). Hence, coarser grains may display more mechanical features in their surfaces than fine-grained grains.

Dune sands

Factor 1 accounts for 42.79% of the total variance in dune sands (Table 5). Conchoidal fractures, V-form grooves, solution pits, and etching are the main surface features grouped in Factor 1. Conchoidal fractures and V-form (linear and curved) grooves are mechanical features, whereas solution pits and etching are chemical features. Mixing of these features suggests the following: (1) dune sands have undergone mechanical abrasion in the aeolian environment, causing conchoidal patterns due to the collision of grains (Krinsley & Donahue 1968); (2) V-form grooves are associated with grains from the beach; and (3) chemical abrasion results from solution pits and etching. These features are associated with the eastern coast dune sands. This is also supported by the fact that eastern coast dune sands have more angular grains than western dune sands, and that diatoms are attached to the quartz grains (Fig. 5G,H). Diatoms on quartz grains are indicative of silica re-precipitation or silica biogenic globules. This feature is produced in pedologic environments and intertidal zones saturated with silica (Higgs 1979; Middleton & Davis 1979). Modal analysis shows that the Po/Mo ratio decreases for both coastal areas and that the Ro/An ratio increases for the western sands and decreases for the eastern sands, indicating the effect of chemical alteration on the quartz grains from the dune. This is due to the fact that the landward decrease in polycrystalline grains is more a consequence of chemical weathering than of mechanical breakage in the dune, and because fine-grained polycrystalline quartz is less chemically stable than monocrystalline quartz. In addition, the landward decrease of the Ro/An ratio in the eastern sands suggests that wind has been unable to generate more rounded quartz in the dune.

CONCLUSIONS

1. Factor 1 for beach sands groups surface features of mechanical abrasion of quartz grains. The Po/Mo high ratio in the beach sands is probably related only to the time of residence, deposition, and transport of polycrystalline quartz in the water. However, the Ro/An ratio landward increase in the western beach sands suggests that they have undergone little mechanical abrasion as compared to the eastern coast beach sands. This implies that the mechanical processes based on petrologic and SEM analyses were only detected for the eastern coast sands.

2. Factor 1 for dune sands groups surface features of mechanical abrasion and chemical corrosion of quartz grains. Northland dune sands have undergone a mixture of mechanical abrasion and chemical attack processes. Mechanical abrasion (conchoidal features and linear and curved groves) and chemical abrasion (solution pits and etching) are more associated with the eastern dune sands than the western dune sands. This is supported by a Po/Mo ratio decrease landwards and a Ro/An ratio decrease landwards. In addition, the presence of diatoms on the quartz grains of the east coast supports the process of chemical precipitation in a high-silica environment.

3. Durability of coarse-grained polycrystalline quartz relative to fine-grained polycrystalline quartz suggests that chemical abrasion exerts control over the quartz type distribution in the Northland dune sands.

ACKNOWLEDGMENTS

Sampling and thin sectioning were carried out during a postdoctoral fellowship at the School of Earth Sciences, Victoria University of Wellington, New Zealand, with funding from CONACyT (Mexico's Council of Science and Technology, project no. 990227). Point-counting and SEM analyses were carried out at the Instituto de Ciencias del Mar y Limnología of the Universidad Nacional Autónoma de México.

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