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Sediment sizes and sources in the cool-water, coastal environment of Adelaide, South Australia

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Abstract

Coastal environment sediments in temperate, cool-water systems were assumed to be siliciclastics until the latter third of last century. This is not surprising as quartz grains dominate most beach sands. Scientists, delving below the sea-surface since ~1980, discovered carbonate grains increase dramatically with water depth. Physical parameters such as tides, storms and currents cause mixing, transport and weathering of the entire package of grains. Sea-floor morphology further alters the ill-conceived perception of a flat surface veneered with even sized, similar grains. Chemical weathering and minor biogenic predation cause further disruption, with anthropogenic activity impinging on the natural cycle in an alarming manner and rate. This project studied 295 samples from the entire beach to 20 m water depth from 22 transects orthogonal to the beach, along the 100 km coastline adjacent to the city of Adelaide, South Australia. Results showed sediment grain-size heterogeneity is widespread, as a result of differences in mineralogy and source, particularly of the biogenic carbonate grains. This has implications for successful beach management strategies. Modern society expects access to pristine beaches during its leisure time, yet industry expects to continue using the sea as a “rubbish dump”. Education concerning the fragility of the shallow sea-floor environment and the sedimentary cycle is urgently needed.

Key words: temperate coastal environments, mineralogy, calcareous benthic biogenic production, erosion effects

SIGNIFICANCE

Humans enjoy the ambience of the coast, particularly if it includes sandy beaches and clean water. Enjoyment of various activities has led to the development of an economically significant tourism industry in addition to the commercial aspects of housing, shipping and fishing. This is seen in the demographics of all countries that have coastlines, and none more so than Australia, where more than 80% of the population live within an hour's drive of the coast.

It follows, then, that it is important to understand the effect that these anthropogenic activities have, if any, upon the natural environment of the coastal region. The sediments veneering the sea floor control the quality of such beaches and their shallow seas (0–20 mwd {mean water depth}). It is mandatory to understand the parameters that control the *in situ* formation and/or sources of these sediments.

SETTING

The city of Adelaide is located on the eastern side of Gulf St Vincent, an inverse estuary (figure 1). Its morphology is constrained by the sea to the west and the fold and thrust N-S trending belt of the Mt Lofty Ranges to the east (JENKINS and SANDIFORD, 1992). The narrow coastal strip has an average width of 30 km, so that the spread of Adelaide over the 150 years since its settlement, has been mainly confined within these boundaries, resulting in a metropolitan area of more than 10^6 people living in a N–S strip 72 km long. Climate is Mediterranean, without large permanent rivers, but with the coastal plain crossed by several ephemeral creeks and minor rivers. The prevailing wind direction is from the southwest, so that the seawater currents flowing into Gulf St Vincent are from the Southern Ocean via Investigator Strait (figure 1). Circulation within the gulf is controlled by the residual of the oceanic 2 m swell and the 2 m amplitude tides. Commonly, sediment grains are carried obliquely shorewards, with the lower energy of the orthogonal waves of the ebb tide giving a net northwards movement of the finer fraction of the sediments, i.e. longshore drift. In summer, seawater density increases northwards due to shallowing and excessive evaporation rates. Wind direction reversals, stemming from the southernmost extent of cyclones, result in a short-lived, south-moving, coast-hugging current pattern. This does not, however, re-equilibrate sediment movement, so that an overall northernwards movement persists. Extensive seagrass meadows, covering the sea floor of the shallow waters from a depth of 1–20 m, act as major baffles and inhibit sediment movement. This pattern has been operating for most of the last 125 Ka (figure 2).

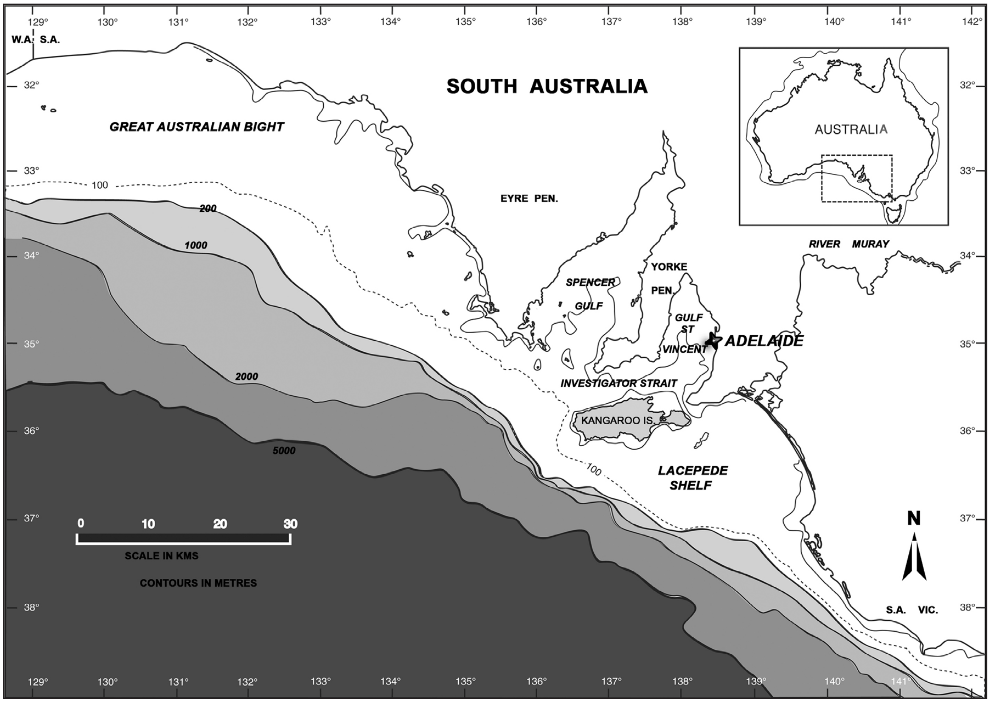

Fig. 1. Location map of study area.

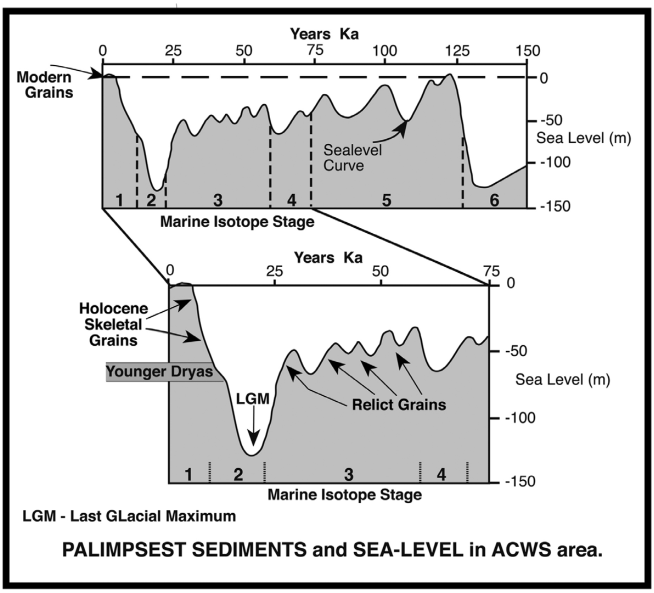

Fig. 2. Sea level over the last 125 Ka. Episodic global glacial events have caused many regressions, with minor still-stands. Only two major warming events have produced major transgressions in Gulf St Vincent (after BELPERIO et al., 1984).

This paper focuses only on the sizes of the sediment grains resulting from these same processes as they are today, although the mineralogy, shape, sources and biogenic implications were facets of the overall research. Other important aspects of the sediments are their role as substrate for algae, grasses and their epiphytes and as the domain of infaunal biota (SHEPHERD and THOMAS, 1982; LUDBROOK, 1984; JAMES et al., 2009) but these were not included in this study. The specific coastal area selected for the study (figure 3) was the strip between the "back of beach" and the -20 m water level, where that was not more than 5 km from the coast.

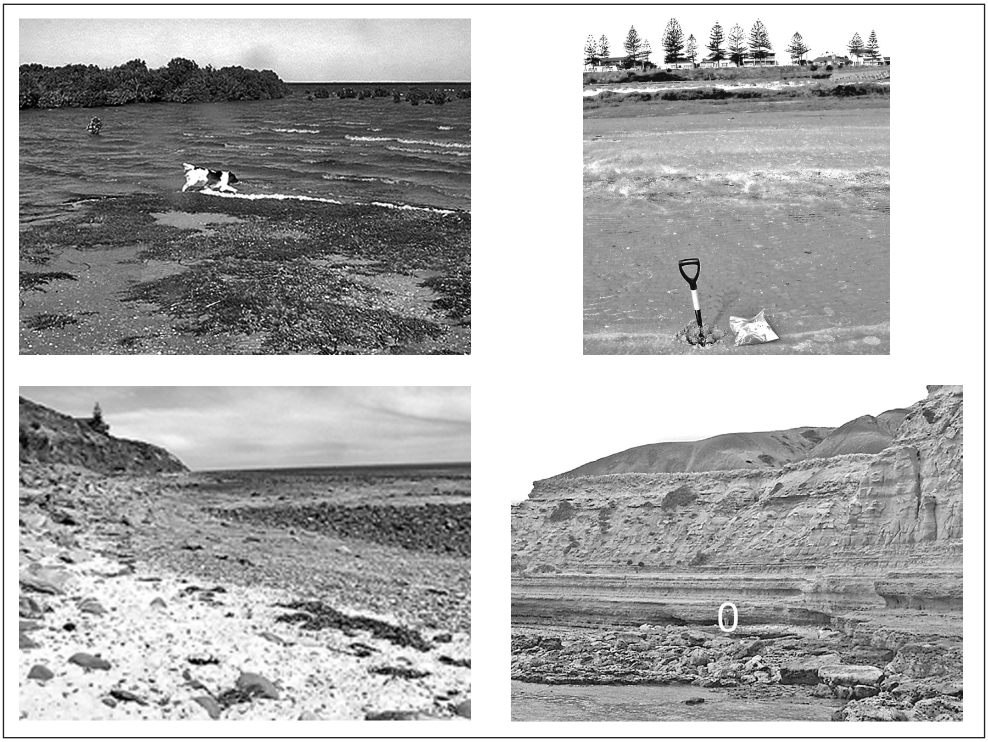

Fig. 3. (a) Zone 1: the mangrove environment, with dog for scale, is a prograding area, with active *Avicennia marina* extending its advance. The pneumatophores trap much of the sediment and detritus carried shorewards, and supports a thriving marine biota. It is interlaced with tidal creeks, which can be almost estuarine in character. These inlets drain the salt marshes landwards.

(b) Zone 2: open sandy beaches. Longshore drift results in build-up of fine sand in the north and sand erosion in the south of the Zone. These wide shallow beaches are mainly in a stable phase. The "back of beach" area is a low partially fixed dune, such as seen here at Largs Bay.

(c) Zone 3: Precambrian cliffs and platform. The eroded siliciclastic rocks are predominantly fine-grained siltstones, with minor sandstones, arkoses and dolostones. The north end shows the eroded beach, the scattered boulders from the cliffs and a modern wave-eroded platform, adjacent to houses that allow all their stormwater, carrying debris, to run into the sea.

An important caveat to add is that results in such studies do not differentiate between naturally-occurring sediments, which includes those debouching on to the sea floor from man-made drainage features, and those artificially dumped or pumped into the area from the beach replenishment scheme, as is the situation in Adelaide. Some data exists about the scheme, but comprehensive records of all sources, material type, dates, tonnages, dumping sites, etc. were not available at the time of this study.

INTRODUCTION

Size of sediment grains, in all environments, is the most important parameter when determining the hydrodynamic activity of sediments, with source (including biogenic), shape and mineralogy lesser factors. Adelaide and its coast have been described by numerous notable scientists, with Howchin and Tate in the late 1800s, followed by many others in the 1900s (e.g. SHEPHERD and SPRIGG 1976; SPRIGG 1979; GOSTIN et al., 1984; BELPERIO et al., 1986, 1988; CANN and GOSTIN 1985; CANN et al., 1988).

Understanding of the sedimentary processes involved in the production, deposition and accumulation of sediments of mixed origin such as those in the study area, i.e. a package of grains predominantly derived from allochthonous terrigenous sources and autochthonous biogenically-produced particles, together with minor contributions from other sources such as physical erosion of the coastline, has undergone major advances during the last two decades. Work on modern mixed carbonate-terrigenous sediments prior to 1980 was based either in modern tropical environments or on earlier work on sediments from bleaker areas, derived from terrigenous sources only. Neither of these models is applicable to the cool-water environment of coastal Adelaide, as in the measurement of grain size, the biogenically-derived grains are constrained by metabolic processes and can vary over many orders of magnitude, e.g. a bryozoan colony may be one sediment grain as a whole cobble-sized dead colony, but upon post-mortem disintegration, it may become 10s to 100s of individual zooids of fine sand (BONE and JAMES, 1993).

METHODOLOGY

The physical characteristics of the sediments veneering the sea floor in coastal regions consist of a number of facets, which are determined both qualitatively and quantitatively. Qualitative data were obtained by photography and observations, both in the field and laboratory. These comprised shape, colour, sorting, variability, local environment and presence of associated biota. Quantitative analyses were made in the laboratory on the field samples, and in this study, centred on grain sizes (Table 1). Subdivision into coarse sand and gravel, medium sand, fine sand and silt and clay fractions was selected to enable interdisciplinary understanding (Table 1).

>2mm	coarse (and larger)
2mm - 0.25mm	medium
0.25mm - 0.063mm	fine
<0.06mm (residue)	very fine (includes silt and clay)

Table 1. Grain size terminology

The area was divided into 4 zones, based on geology and geomorphology (figure 3; Table 2). Twenty two transects (figure 4) were positioned orthogonal to the coast, with 8 depth-determined sample positions along the transects: supratidal, intertidal, and at depths of 1 m, 2 m, 5 m, 10 m, 15 m and 20 m, where possible. Sampling sites covered all facies within the area, from the coast to up to 5 km offshore. Sites were sampled mid-summer and mid-winter. Sample numbering (Table 3) and abbreviations (Table 4) were devised to enable systematic and easy identification of each sample.

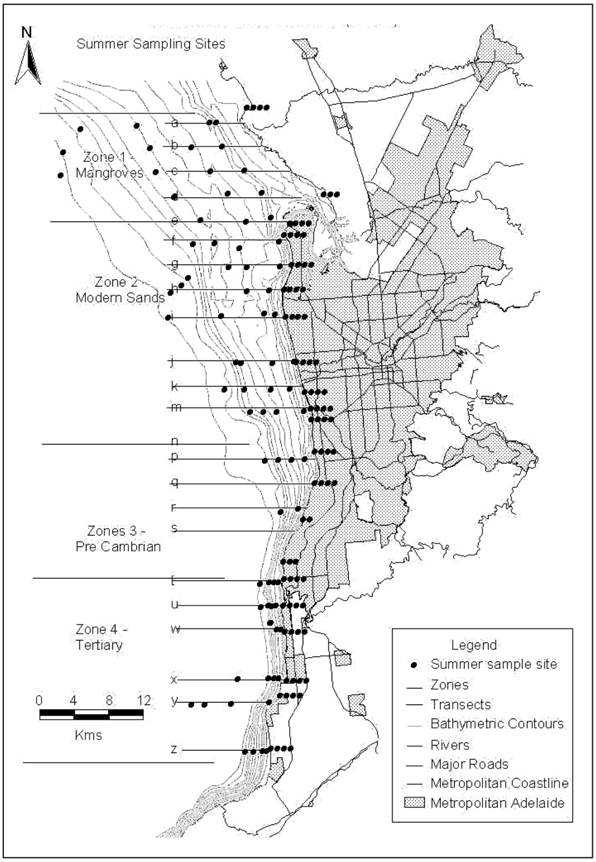

Fig. 4. Map of the Adelaide coastal area, showing bathymetry and positions of study zones 1-4, transects and sample sites. The sites apparently on land are artefacts of the scale of the map. Transect line shifts resulted from navigation problems. Similarly, marine and weather conditions caused slight shifts between some of the summer and winter sites.

Zone 1 – Mangroves

1-a	*Port Gawler North*	marks N extent of the study area, typical of zone – mangroves, marshes, cheniers, sabkhas
1-b	*Gawler River Estuary*	entry point of fine-grained siliciclastic fluvial load
1-c	*North of Barker Inlet*	interface between mangroves and sand area
1-d	*Mid Barker Inlet*	transect starts due N of Pelican Point Power Station, in middle of dredged shipping lane
1-e	*Outer Harbour*	will reflect Barker Inlet impact on sea-floor sediment

Zone 2 – Modern Sands

2-f	*North Haven*	marina effects and sand deposition depot centre
2-g	*Largs Bay*	deposition depot centre and offshore calcrete as basement
2-h	*Semaphore Beach*	offshore calcrete as basement
2-i	*Henley Beach*	typical of zone
2-j	*West Beach*	N of River Torrens mouth, anthropogenic influence
2-k	*North of Barcoo Inlet*	anthropogenic influence, sewage outfall area
2-l	*North of Patawalonga Creek Mouth*	current scouring, anthropogenic influence – shipping channel, extensive breakwater
2-m	*South of Glenelg Breakwater*	sand deposition depot centre, natural and against breakwater
2-n	*Brighton/Somerton*	typical of zone

Zone 3 - Precambrian Siliciclastic Cliffs

3-p	*Marino Rocks*	typical of a rock-strewn sea floor
3-q	*Hallett Cove / Waterfall Creek*	disturbed Permian Till load and Precambrian cliffs
3-r	*Port Stanvac*	anthropogenic influence, maritime disturbance
3-s	*O'Sullivans Beach*	Christies Beach Sewage Outfall, marina

Zone 4 – Tertiary Limestone Cliffs

4-t	*Christies Beach*	N extent of carbonate contribution from limestone
4-u	*Port Noarlunga / Onkaparinga Estuary*	mix of carbonate contribution from coastal area and Precambrian siliciclastic contribution from fluvial load
4-w	*Moana North*	off the beach, numerous stormwater entry points
4-x	*Maslin Beach*	typical of zone
4-y	*Snapper Point*	rapid bathymetry change at reef drop-off, prolific calcareous biota
4-z	*Sellicks Beach*	S extent of study area, steep shoreface, large load from gullying of Adelaide Hills outwash fans

Table 2. Rationale for selection of Zones and Transects

ACWS	= Adelaide Coastal Waters Study
(W)	= winter
1	= zone, starting from the North (mangroves)
a	= transect number, starting from the North (N-most transect)
3	= sample on the transect, starting from the East (back of beach)
bk	= bulk (raw sample)
(1)	= number of photograph in sequence of photographs of subject
(x10)	= magnification used for photograph

Table 3. Numbering system for sediment grain size samples
number: ACWS (W)1a-3-bk(1)(x10)

Water Depth Number
1 = back of beach
2 = mid tide
3 = 1 m
4 = 2 m
5 = 5 m
6 = 10 m
7 = 15 m
8 = 20 m
Size fraction Term
bk = bulk ("composite")
cs = coarse (coarse sand/gravel)
med = medium (medium sand)
fn = fine (fine sand)
v.fn = silt and clay
Magnification and Field of View of Images
x6.2=25 mm
x10=10 mm
x20=6 mm
x32=4 mm

Table 4. Abbreviations used in description and labelling of samples

FIELD WORK

Field work sampling consisted of two techniques for each transect: either sampling from the beach and shallow waters, using snorkeling if needed, or sampling by dredging or SCUBA from a boat. Ideally, 2 litre samples were collected. Log Book entries were made of the following: date, transect/co-ordinates, site number/co-ordinates, depth, time (CST), surface and bottom temperature, surface and bottom salinity, equipment deployed (dredge, SCUBA or hand), photographs taken, recovery volume (2 litre goal), number and type of splits, fresh and wet colour, field description of sample, living biota (in sample, on sea floor) and any deviation(s) from normal procedure. Sea-floor factors such as rock cover or pavement and/or the sea-state sometimes resulted in the Captain deciding a position shift was mandatory. Similarly, weather vagaries influenced the sequence and timing of sampling, sometimes resulting in its cessation before completion of a transect. It was not always possible to return to the exact same position at a later date.

LABORATORY WORK

Sample preparation

The 295 samples collected were washed three times within 24 hours of collection, allowed to settle for 30 sec, decanted and the residue saved for its clay-silt fraction. This procedure removed all salt, which would otherwise crystallise on to the grains as the sample dried and skew weights made later. Samples were allowed to air-dry. The residue was dried and then thoroughly mixed into the bulk sample.

Observations recorded

Munsell colour codes, subjective colour of wet and dry sample, photographs taken of each, overall grain size, shape, sorting, apparent mineralogy, relict components, living biota, dead biota, fossils and other, e.g. anthropogenic, such as coke cans, were all noted.

Grain size analysis

Standard quartering techniques were used to produce homogenous samples from heterogeneous original samples. Half of the dry bulk sample was weighed and wet sieved through a bank of >2 mm, >0.25 mm, >0.063 and bottom collection pan sieves. The residue was allowed to settle for three days, then decanted. The four fractions were dried and weighed (figure 5), and the percentage of each fraction calculated. Two 1 cc samples were taken from each fraction, with one sample for microscope analysis and the other for carbonate digestion.

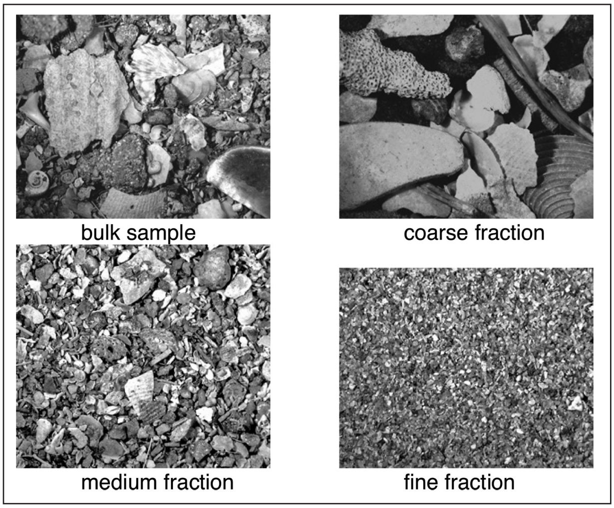

Fig. 5. The four size fractions of sample ACWS 3p-6X10, with the bulk sample typical of a mixed sea-floor sample, but with the medium and fine fractions skewing from the mixed category. The bulk and medium fractions appear to be volumetrically dominated by very large, angular, calcareous biogenic grains but, numerically, grains are “mixed”. Coarse is dominated by calcareous biogenic grains. Fine is dominated by smooth quartz grains, with a sprinkling of larger biogenic, angular grains.

Microscope analysis

The number of unidentified biogenic fragments; bryozoan, bivalve, gastropod, echinoid, calcareous algal, foraminifer and calcareous worm tube grains; quartz grains; relict grains – orange, black, grey, brown; and heavy minerals was counted in one of the 1 cc samples from each fraction of each sample. This data was used in interpreting the results of this study, but is not included here but is in a separate paper (see BONE et al., 2007).

Mineralogy analysis

The other 1 cc sample was weighed, soaked overnight in sodium hypochlorite to dissolve organic material, then washed, dried and weighed. The residue was soaked in 10% HCl until effervescence ceased to remove all carbonate, washed, dried and weighed. The residue was then passed through a Franz Magnetic Separator, to remove the heavy minerals. The remaining siliciclastics were weighed. These procedures enabled the calculation of the different minerals in each sample. This data was used in the overall interpretation of this study (see BONE et al., 2007).

RESULTS

Maps of the distribution and abundance of different grain sizes for summer and winter were plotted (figures 6, 7, 8 and 9) to enable immediate visualisation of the distribution of the different size fractions throughout the area, based on the percentage of each fraction: abundant >35%, common 10–35%, present 2–10%, rare <2%. The weight and percentage data for the 2,161 laboratory grain size analyses of the summer samples are shown in Table 5, but only those from one transect from each zone for the winter samples are given (Table 6), as the differences were insignificant.

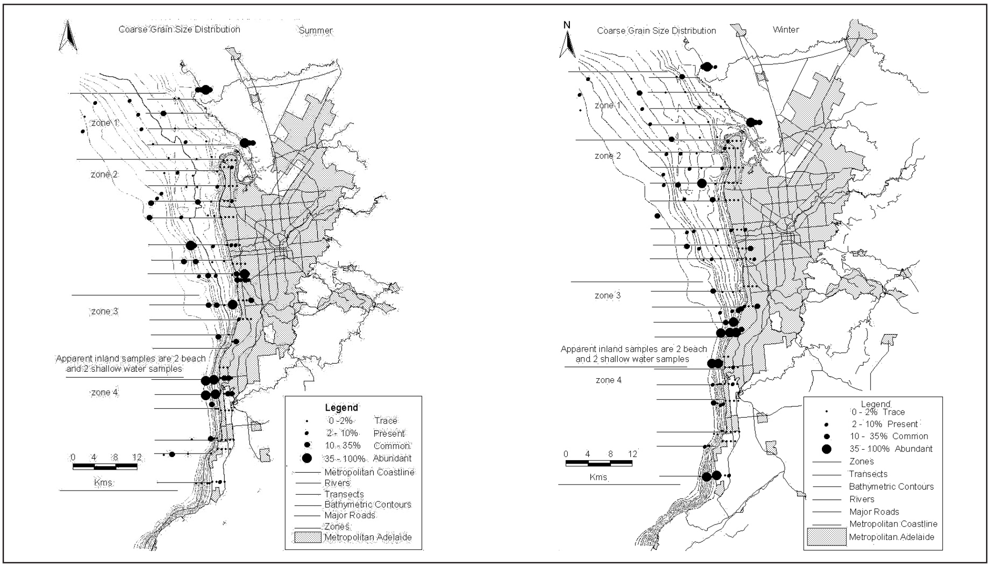

Fig. 6. Distribution of the coarse fraction of the sediment samples in (a) Summer, and (b) Winter.

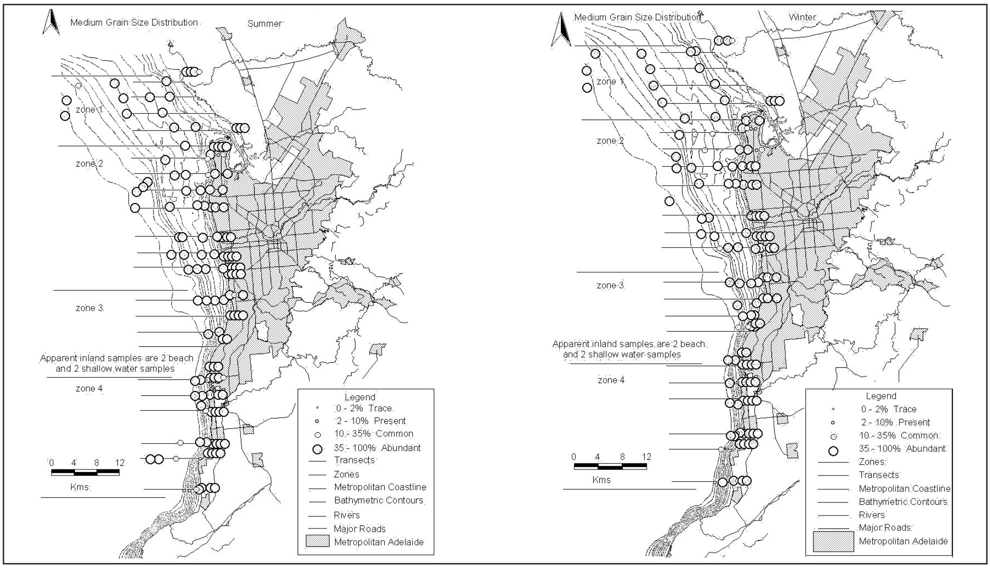

Fig. 7. Distribution of the medium fraction of the sediment samples in (a) Summer, and (b) Winter.

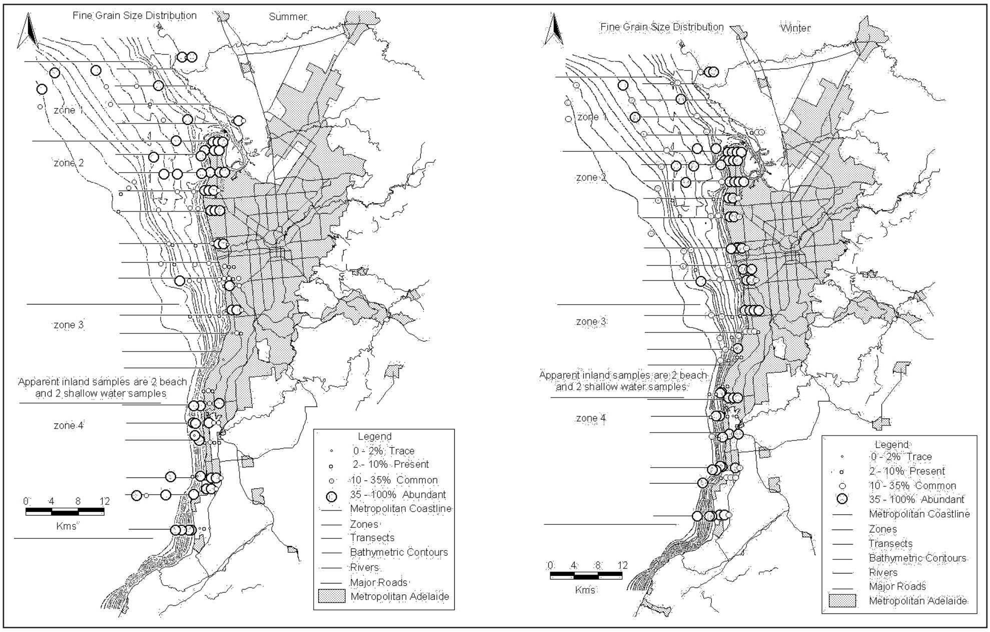

Fig. 8. Distribution of the fine fraction of the sediment samples in (a) Summer, and (b) Winter.

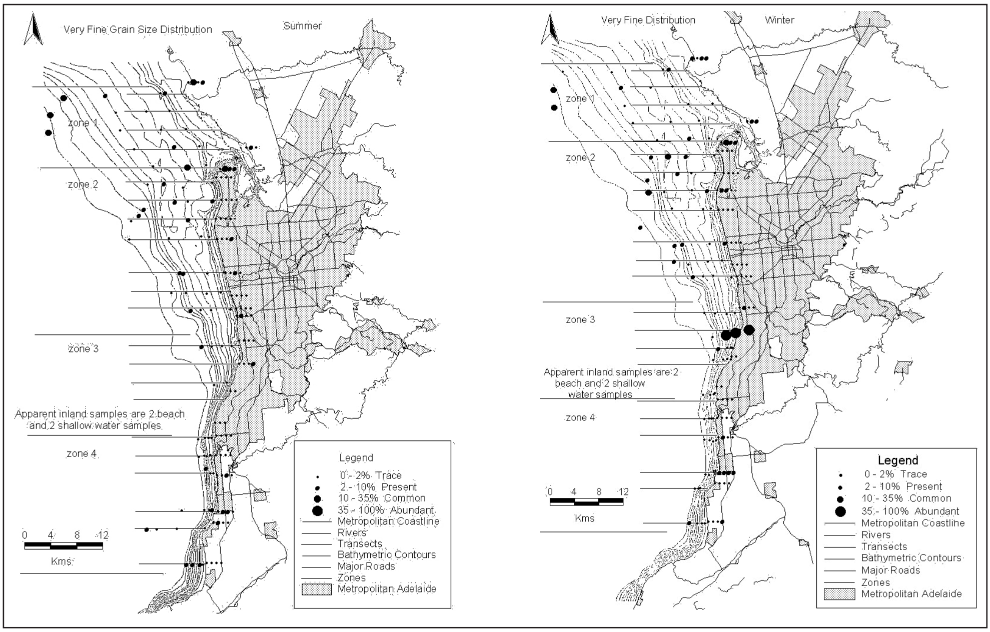

Fig. 9. Distribution of the very fine fraction of the sediment samples in (a) Summer, and (b) Winter.

Table 5. Grain size data - summer samples. No data in a sequence indicates no sample or it was too small to process. There were no summer samples for Marino, 2q.

Transect	No.	Sample wt gm	Coarse wt gm	Medium wt gm	Fine wt gm	V fine wt gm	Coarse %	Medium %	Fine %	V Fine %
Port	1a-1	364.14	38.39	232.51	87.44	5.80	10.54	63.85	24.01	1.59
Gawler	1a-1	154.19	27.32	45.64	73.06	8.17	17.72	29.60	47.38	5.30
North	1a-2	232.76	122.78	86.49	21.16	2.33	52.75	37.16	9.09	1.00
	1a-3	184.44	97.19	77.02	8.11	2.12	52.69	41.76	4.40	1.15
	1a-4	132.66	13.31	51.16	54.60	13.59	10.03	38.56	41.16	10.24
	1a-5	267.55	3.23	180.00	76.61	7.71	1.21	67.28	28.63	2.88
	1a-7	276.18	18.28	145.49	99.53	12.88	6.62	52.68	36.04	4.66
	1a-8	152.50	3.48	41.03	56.52	51.47	2.28	26.90	37.06	33.75
Gawler	1b-5	315.00	0.53	118.08	194.31	2.08	0.17	37.49	61.69	0.66
River	1b-6	68.40	20.75	31.59	15.99	0.07	30.34	46.18	23.38	0.10
Estuary	1b-7	301.47	11.05	195.20	95.22	0.00	3.67	64.75	31.59	0.00
	1b-8	208.32	2.71	80.95	74.13	50.53	1.30	38.86	35.58	24.26

Transect	No.	Sample wt gm	Coarse wt gm	Medium wt gm	Fine wt gm	V fine wt gm	Coarse %	Medium %	Fine %	V Fine %
St Kilda	1c-1	190.61	96.62	87.32	7.84	-1.17	50.69	45.81	4.11	-0.61
	1c-2	208.65	35.03	129.50	41.78	2.34	16.79	62.07	20.02	1.12
	1c-3	136.65	27.23	48.10	51.65	9.67	19.93	35.20	37.80	7.08
	1c-6	86.47	1.33	77.39	7.43	0.32	1.54	89.50	8.59	0.37
	1c-7	324.55	16.97	220.05	83.16	4.37	5.23	67.80	25.62	1.35
	1c-8	234.48	10.01	97.70	76.67	50.10	4.27	41.67	32.70	21.37
Barker Inlet	1d-5	280.86	4.31	152.67	120.14	3.74	1.53	54.36	42.78	1.33
	1d-6	106.73	9.67	66.36	27.43	3.27	9.06	62.18	25.70	3.06
Outer Harbour	1e-1	323.84	0.09	210.99	108.08	4.68	0.03	65.15	33.37	1.45
	1e-2	311.20	0.23	111.56	186.01	13.40	0.07	35.85	59.77	4.31
	1e-3	322.99	0.27	156.18	156.25	10.29	0.08	48.35	48.38	3.19
	1e-4	361.77	2.05	131.65	177.47	50.60	0.57	36.39	49.06	13.99
	1e-6	390.99	1.35	204.19	142.31	43.14	0.35	52.22	36.40	11.03
North Haven	2f-1	372.46	0.45	197.23	171.95	2.83	0.12	52.95	46.17	0.76
	2f-2	306.70	7.00	79.54	216.46	3.70	2.28	25.93	70.58	1.21
	2f-3	188.69	0.18	9.10	176.18	3.23	0.10	4.82	93.37	1.71
	2f-5	294.11	0.11	32.52	259.81	1.67	0.04	11.06	88.34	0.57
	2f-7	244.93	5.67	90.77	133.40	15.09	2.31	37.06	54.46	6.16
Largs Bay	2g-1	347.11	6.37	161.89	177.35	1.50	1.84	46.64	51.09	0.43
	2g-2	345.06	4.27	134.07	205.84	0.88	1.24	38.85	59.65	0.26
	2g-3	184.69	2.02	8.89	172.91	0.87	1.09	4.81	93.62	0.47
	2g-5	230.96	14.57	79.47	132.11	4.81	6.31	34.41	57.20	2.08
	2g-6	134.21	2.24	68.00	62.43	1.54	1.67	50.67	46.52	1.15
	2g-7	265.56	0.73	95.12	157.62	12.09	0.27	35.82	59.35	4.55
	2g-8	253.08	24.58	162.82	49.53	16.15	9.71	64.34	19.57	6.38
Semaphore	2h-1	383.57	0.17	207.84	172.00	3.56	0.04	54.19	44.84	0.93
	2h-2	398.40	11.95	293.33	91.23	1.89	3.00	73.63	22.90	0.47
	2h-3	337.53	0.21	3.65	331.77	1.90	0.06	1.08	98.29	0.56
	2h-4	288.16	0.11	2.76	282.98	2.31	0.04	0.96	98.20	0.80
	2h-5	367.38	2.96	286.64	73.14	4.64	0.81	78.02	19.91	1.26
	2h-6	226.94	79.39	109.94	30.00	7.61	34.98	48.44	13.22	3.35
	2h-7	246.68	30.37	207.29	5.25	3.77	12.31	84.03	2.13	1.53
	2h-8	243.38	11.42	145.24	62.94	23.78	4.69	59.68	25.86	9.77
Grange	2i-1	378.10	0.10	279.32	95.63	3.05	0.03	73.87	25.29	0.81
	2i-2	366.11	3.59	220.51	132.02	9.99	0.98	60.23	36.06	2.73
	2i-3	353.37	2.51	103.70	241.71	5.45	0.71	29.35	68.40	1.54
	2i-4	384.51	0.31	199.98	179.12	5.10	0.08	52.01	46.58	1.33

Transect	**No.**	**Sample wt gm**	**Coarse wt gm**	**Medium wt gm**	**Fine wt gm**	**V fine wt gm**	**Coarse %**	**Medium %**	**Fine %**	**V Fine %**
	2i-5	374.93	1.23	312.38	56.08	5.24	0.33	83.32	14.96	1.40
	2i-6	211.24	3.45	153.37	51.76	2.66	1.63	72.60	24.50	1.26
	2i-7	122.70	5.14	100.77	15.92	0.87	4.19	82.13	12.97	0.71
	2i-8	300.77	35.41	247.39	12.62	5.35	11.77	82.25	4.20	1.78
Henley	2j-1	379.87	0.25	363.75	13.29	2.58	0.07	95.76	3.50	0.68
Beach	2j-2	357.58	0.73	328.83	23.20	4.82	0.20	91.96	6.49	1.35
	2j-3	370.00	17.51	182.86	160.28	9.35	4.73	49.42	43.32	2.53
	2j-4	312.55	6.89	127.76	173.64	4.26	2.20	40.88	55.56	1.36
	2j-5	320.65	4.49	277.74	34.76	3.66	1.40	86.62	10.84	1.14
	2j-6	368.58	12.17	335.48	18.45	2.48	3.30	91.02	5.01	0.67
	2j-7(1)	204.63	77.17	96.49	25.05	5.92	37.71	47.15	12.24	2.89
	2j-8	282.16	54.13	195.79	26.16	6.08	19.18	69.39	9.27	2.15
West	2k-1	391.90	6.16	378.91	6.00	0.83	1.57	96.69	1.53	0.21
Beach	2k-2	361.73	0.23	352.23	8.60	0.67	0.06	97.37	2.38	0.19
	2k-3	393.26	2.15	347.25	38.66	5.20	0.55	88.30	9.83	1.32
	2k-4	353.76	0.68	266.07	84.79	2.22	0.19	75.21	23.97	0.63
	2k-5	369.54	0.15	281.20	82.39	5.80	0.04	76.09	22.30	1.57
	2k-6	358.72	0.04	257.55	95.51	5.62	0.01	71.80	26.63	1.57
	2k-7	333.43	90.34	229.94	8.90	4.25	27.09	68.96	2.67	1.27
	2k-8	386.20	69.74	260.44	51.56	4.46	18.06	67.44	13.35	1.15
Glenelg	2L-1	394.18	72.81	261.18	58.17	2.02	18.47	66.26	14.76	0.51
North	2L-2	377.31	7.58	306.78	58.11	4.84	2.01	81.31	15.40	1.28
	2L-3	478.40	203.08	260.83	13.33	1.16	42.45	54.52	2.79	0.24
	2L-4	302.96	4.25	215.94	79.49	3.28	1.40	71.28	26.24	1.08
Glenelg	2m-1	360.30	0.43	270.27	87.00	2.60	0.12	75.01	24.15	0.72
South	2m-2	406.11	23.29	289.30	89.00	4.52	5.73	71.24	21.92	1.11
	2m-3	441.71	45.97	288.84	103.04	3.86	10.41	65.39	23.33	0.87
	2m-4	357.63	9.28	169.64	166.94	11.77	2.59	47.43	46.68	3.29
	2m-5	417.29	0.32	298.37	112.12	6.48	0.08	71.50	26.87	1.55
	2m-6	281.24	61.51	204.48	13.88	1.37	21.87	72.71	4.94	0.49
	2m-7	136.97	10.41	102.81	22.92	0.83	7.60	75.06	16.73	0.61
	2m-8	339.57	50.63	283.57	2.72	2.65	14.91	83.51	0.80	0.78
Brighton	2n-5	349.72	186.93	151.17	9.58	2.04	53.45	43.23	2.74	0.58
North	2n-6	398.11	3.43	375.07	17.58	2.03	0.86	94.21	4.42	0.51
	2n-7	373.78	70.06	295.54	5.62	2.56	18.74	79.07	1.50	0.68
	2n-8	139.46	41.67	81.94	12.73	3.12	29.88	58.76	9.13	2.24

Transect	No.	Sample wt gm	Coarse wt gm	Medium wt gm	Fine wt gm	V fine wt gm	Coarse %	Medium %	Fine %	V Fine %
Brighton South	3p-1	402.95	0.11	368.44	33.52	0.88	0.03	91.44	8.32	0.22
	3p-2	418.51	49.68	308.04	60.00	0.79	11.87	73.60	14.34	0.19
	3p-3	349.35	3.70	61.84	281.30	2.51	1.06	17.70	80.52	0.72
	3p-4	266.94	0.38	71.72	191.13	3.71	0.14	26.87	71.60	1.39
Kingston Park	3q-1	380.22	36.08	336.49	2.51	5.14	9.49	88.50	0.66	1.35
	3q-2	392.01	0.23	351.70	32.20	7.88	0.06	89.72	8.21	2.01
	3q-3	389.25	1.09	307.06	74.56	6.54	0.28	78.89	19.15	1.68
	3q-4	413.88	2.68	404.65	4.68	1.87	0.65	97.77	1.13	0.45
Hallett Cove	3s-1	316.88	0.12	311.91	3.40	1.45	0.04	98.43	1.07	0.46
	3s-3	433.63	144.89	281.81	6.07	0.86	33.41	64.99	1.40	0.20
O' Sullivan Beach	4t-1a	326.11	0.32	301.65	22.88	1.26	0.10	92.50	7.02	0.39
	4t-2a	292.06	0.00	276.86	14.55	0.65	0.00	94.80	4.98	0.22
	4t-3a	429.25	0.90	354.01	72.40	1.94	0.21	82.47	16.87	0.45
Christies Beach	4t-1	411.29	0.02	331.43	77.74	2.10	0.00	80.58	18.90	0.51
	4t-2	432.65	74.81	272.28	84.17	1.39	17.29	62.93	19.45	0.32
	4t-3	442.89	102.68	249.61	88.49	2.11	23.18	56.36	19.98	0.48
	4t-4	399.28	1.96	134.51	260.41	2.40	0.49	33.69	65.22	0.60
	4t-5	373.82	0.38	46.28	324.62	2.54	0.10	12.38	86.84	0.68
	4t-6	457.09	338.29	106.37	10.80	1.63	74.01	23.27	2.36	0.36
	4t-7	398.82	0.54	175.86	216.95	5.47	0.14	44.10	54.40	1.37
	4t-8	390.43	177.65	207.73	3.41	1.64	45.50	53.21	0.87	0.42
Port Noarlunga South	4u-1	387.26	0.65	371.20	13.71	1.70	0.17	95.85	3.54	0.44
	4u-2	395.12	1.42	381.82	9.95	1.93	0.36	96.63	2.52	0.49
	4u-3	354.07	0.64	314.32	29.13	9.98	0.18	88.77	8.23	2.82
	4u-4	325.94	2.17	269.39	48.42	5.96	0.67	82.65	14.86	1.83
	4u-6	146.10	1.55	38.07	104.81	1.67	1.06	26.06	71.74	1.14
	4u-7	322.95	0.29	98.33	216.88	7.45	0.09	30.45	67.16	2.31
	4u-8	401.66	139.49	259.53	2.05	0.59	34.73	64.61	0.51	0.15
Seaford/ Moana	4w-1	365.06	0.01	326.20	37.22	1.63	0.00	89.36	10.20	0.45
	4w-2	399.91	3.10	327.84	63.56	5.41	0.78	81.98	15.89	1.35
	4w-3	326.04	0.01	180.17	135.67	10.19	0.00	55.26	41.61	3.13
	4w-4	353.02	0.07	219.96	123.78	9.21	0.02	62.31	35.06	2.61
	4w-5	636.56	7.29	124.20	505.07	0.00	1.15	19.51	79.34	0.00
	4w-6	398.89	0.22	246.32	143.04	9.31	0.06	61.75	35.86	2.33
	4w-8	254.90	33.89	210.40	9.59	1.02	13.30	82.54	3.76	0.40

Transect	No.	Sample wt gm	Coarse wt gm	Medium wt gm	Fine wt gm	V fine wt gm	Coarse %	Medium %	Fine %	V Fine %
Maslins Beach	4x-1	431.81	0.00	378.72	46.31	6.78	0.00	87.71	10.72	1.57
	4x-2	389.25	4.54	338.57	39.90	6.24	1.17	86.98	10.25	1.60
	4x-3	393.79	0.77	174.82	212.10	6.10	0.20	44.39	53.86	1.55
	4x-4	388.78	1.44	205.30	167.04	15.00	0.37	52.81	42.97	3.86
	4x-5	309.99	0.63	24.72	279.52	5.12	0.20	7.97	90.17	1.65
	4x-6	317.85	0.70	45.04	272.11	0.00	0.22	14.17	85.61	0.00
	4x-7	398.50	106.64	172.25	116.89	2.72	26.76	43.22	29.33	0.68
	4x-8	349.47	1.70	125.83	214.13	7.81	0.49	36.01	61.27	2.23
Port Willunga/ Aldinga Beach	4y-1	396.87	0.58	388.86	6.16	1.27	0.15	97.98	1.55	0.32
	4y-2	434.16	7.70	417.66	8.14	0.66	1.77	96.20	1.87	0.15
	4y-3	420.90	16.23	388.28	13.50	2.89	3.86	92.25	3.21	0.69
	4y-5	254.73	0.14	154.64	95.75	4.20	0.05	60.71	37.59	1.65
	4y-6	355.43	0.10	67.11	277.69	10.53	0.03	18.88	78.13	2.96
	4y-7	230.65	1.80	18.70	205.39	4.76	0.78	8.11	89.05	2.06
	4y-8	331.26	0.95	29.47	291.24	9.60	0.29	8.90	87.92	2.90
Sellicks Beach	4z-1	450.23	100.99	259.16	87.92	2.16	22.43	57.56	19.53	0.48
	4z-2	428.95	35.43	294.35	93.28	5.89	8.26	68.62	21.75	1.37
	4z-3	352.93	22.41	261.77	63.73	5.02	6.35	74.17	18.06	1.42
	4z-4	357.07	0.30	248.08	103.05	5.64	0.08	69.48	28.86	1.58
	4z-5	368.36	0.07	5.21	361.30	1.78	0.02	1.41	98.08	0.48
	4z-6	357.41	0.09	3.49	352.35	1.48	0.03	0.98	98.58	0.41
	4z-8	318.29	0.16	7.30	289.31	21.52	0.05	2.29	90.90	6.76

Table 6. Winter Grain Size Data (same parameters as Table 5)

Transect	No.	Sample wt gm	Coarse wt gm	Medium wt gm	Fine wt gm	V fine wt gm	Coarse %	Medium %	Fine %	V Fine %
Port Gawler North	1a-1	323.54	75.07	146.13	89.38	12.96	23.20	45.17	27.63	4.01
	1a-2.1	297.34	24.66	103.48	159.30	9.90	8.29	34.80	53.58	3.33
	1a-2.2	290.47	23.95	181.90	76.58	8.04	8.25	62.62	26.36	2.77
	1a-3	170.35	106.97	53.34	7.65	2.39	62.79	31.31	4.49	1.40
	1a-4	129.15	33.57	47.47	36.84	11.27	25.99	36.76	28.52	8.73
	1a-5	337.37	2.20	308.05	25.61	1.51	0.65	91.31	7.59	0.45
	1a-6	283.74	0.28	178.23	103.16	2.07	0.10	62.81	36.36	0.73
	1a-7	120.61	8.67	80.65	28.93	2.36	7.19	66.87	23.99	1.96
	1a-8	175.05	3.42	61.77	71.58	38.28	1.95	35.29	40.89	21.87
Semaphore	2h-1	404.46	0.13	301.47	99.44	3.42	0.03	74.54	24.59	0.85
	2h-2	371.89	4.35	273.17	90.09	4.28	1.17	73.45	24.22	1.15
	2h-3	401.84	2.12	191.39	198.10	10.23	0.53	47.63	49.30	2.55
	2h-4	277.41	0.08	18.04	251.95	7.34	0.03	6.50	90.82	2.65

Transect	No.	Sample wt gm	Coarse wt gm	Medium wt gm	Fine wt gm	V fine wt gm	Coarse %	Medium %	Fine %	V Fine %
	2h-5	448.00	3.40	389.41	44.64	10.55	0.76	86.92	9.96	2.35
	2h-6	269.81	146.99	119.19	1.58	2.05	54.48	44.18	0.59	0.76
	2h-7	273.33	72.31	185.23	13.24	2.55	26.46	67.77	4.84	0.93
	2h-8	298.80	16.20	161.64	83.14	37.82	5.42	54.10	27.82	12.66
Brighton	3p-1	410.90	0.12	175.68	232.84	2.26	0.03	42.75	56.67	0.55
	3p-2	425.34	2.54	244.94	174.97	2.89	0.60	57.59	41.14	0.68
	3p-3	367.39	3.95	94.48	266.58	2.38	1.08	25.72	72.56	0.65
	3p-4	379.97	0.70	193.01	166.34	19.92	0.18	50.80	43.78	5.24
	3p-5	359.00	0.43	343.27	12.32	2.98	0.12	95.62	3.43	0.83
	3p-6	401.65	5.41	386.70	8.16	1.38	1.35	96.28	2.03	0.58
	3p-7	384.58	5.81	311.32	61.66	5.79	1.51	80.95	16.03	1.51
	3p-8	239.11	46.33	151.82	37.09	3.87	19.38	63.49	15.51	1.62
Sellicks Beach	4z-1	505.55	194.67	260.11	48.61	2.16	38.51	51.45	9.62	0.43
	4z-2	355.89	33.23	253.88	60.61	8.17	9.34	71.34	17.03	2.30
	4z-3	339.19	0.21	164.77	170.13	4.08	0.06	48.58	50.16	1.20
	4z-4	362.17	0.30	90.67	264.15	7.05	0.08	25.04	72.94	1.95
	4z-5	393.44	0.00	0.83	390.64	1.97	0.00	0.21	99.29	0.50
	4z-6	405.05	0.01	4.46	397.90	2.68	0.00	1.10	98.23	0.66
	4z-7	360.91	205.77	146.82	6.43	1.89	57.01	40.68	1.78	0.52
	4z-8	169.08	0.12	7.40	153.09	8.47	0.07	4.38	90.54	5.01

Time; sample site and number; depth; coordinates; temperature; weather; sea-state; weather previous day; volume of sediment collected; colour of sediment; living and dead biota present; general description of sediment were also recorded and tabulated for each site (see BONE et al., 2007).

All size fractions from each sample were photographed, with multiple exposures where necessary. The samples were not high-graded in any way to bias any aspect.

Underwater photographs of 14 sample sites showed the heterogeneity in the nature of the sea floor and its veneer of sediments (figure 10). Parameters such as colour (wet), relative grain size, variability, sorting, rocks and biota present, geomorphic features of the sea floor are all accurately recorded by such methods, and allow comparisons with the samples collected for verification of interpretations.

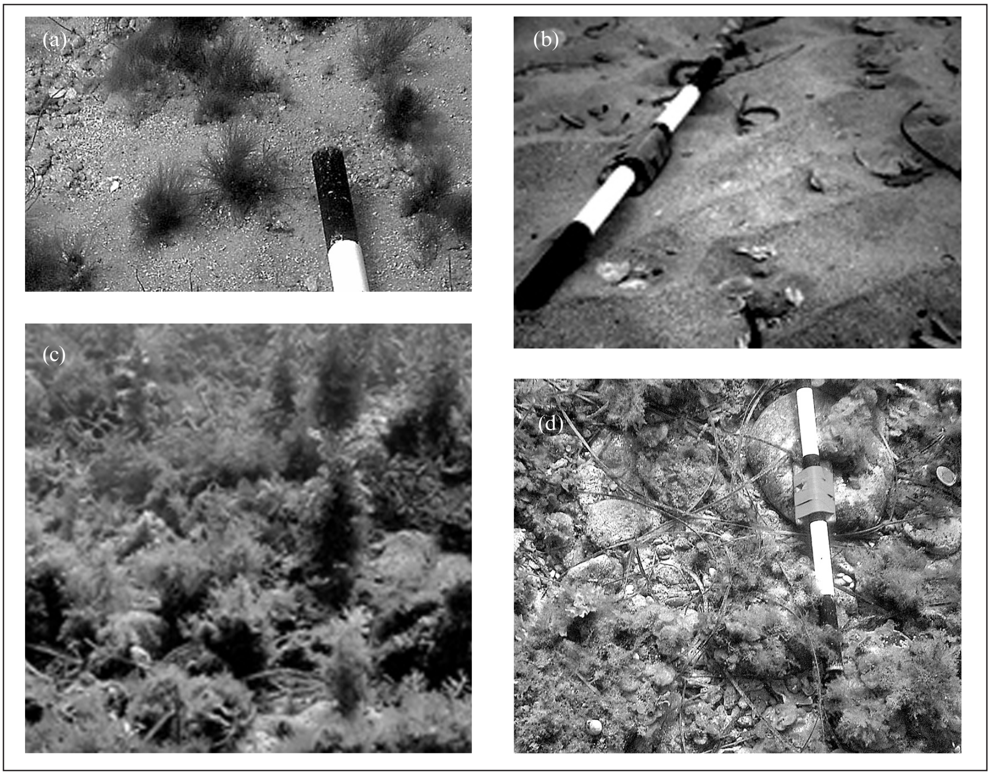

Fig. 10. (a) Zone 2 shows the result of sand dredging for beach replenishment. It will be many decades before the Posidonia shows any sign of re-establishment unless artificial replanting is employed. Many patches in the other zones are veneered with rippled, quartz-rich, medium-grained sand. This environment has little living epifauna but a rich infauna population of invertebrates. Scale bar in 10 cm increments.

(b) The deeper waters (>3 mwd) of zones 1 and 2 and from -1 m in Zone 3 have dense thickets of brown algae. These thickets provide a suitable environment for a variety of benthic invertebrates, but prevent the re-establishment of sea-grasses.

(c) Cobbles from the Precambrian bedrock are typical of shallow areas of Zone 3. They are encrusted with coralline algae and are substrate for soft algae. A few calcareous epiphyte-encrusted blades of dead Posidonia are entangled in the algae, along with various-sized fragments of molluscs. Scale bar in 10 cm increments.

DISCUSSION

General

The physical characteristics of the sediments veneering the sea floor in the Adelaide area were as expected: they are typical of cool water (temperate) environments (JAMES and CLARKE, 1997 and references therein) such as those found across the southern margin of Australia (GOSTIN et al., 1988; JAMES et al., 1992, 1997, 2001; FULLER et al., 1994) but with the addition of minor anthropogenetically contributed grains and of major ecological disturbances. The latter are significant in that they break the natural cyclic behaviour of the temperate environment cool-water carbonate system.

Inshore sediments of such systems are mixed carbonate and siliciclastic sands, with varying amounts of mud and gravel. Carbonate grains are autochthonous and biogenic in origin and allochthonous quartz grains dominate the siliciclastics. This mix produces predominantly medium-sized, rounded, quartz-rich sand beaches with nearshore healthy sea-grass meadows in carbonate-rich sediments (WOMERSLEY, 1984). These meadows support a high diversity and a dense distribution of benthic biota, which is dominated by calcareous invertebrates (SHEPHERD and THOMAS, 1982) and sea-grasses and algae, particularly coralline algae (WOMERSLEY, 1984). Post-mortem remains of the biota produces carbonate biofragments, which either remain *in situ* or are transported elsewhere within the system.

Grain Size – Carbonate Grains

Variability in grain size of the bulk sediments is mainly a function of the ubiquitous carbonate material (figure 5). Carbonates are relatively soft minerals (3 on Moh's hardness scale) with excellent rhombohedral cleavage, and so are easily broken. Biogenic erosion is also significant, being caused by predation of the calcareous biota or its use as a substrate or home by other biota. This selective weathering, e.g. the crunching of a large mollusc by a ray certainly produces numerous coarse grains, is of lesser significance and is not discussed further. Thus, the size of the carbonate fragments that persist in the sediment are mainly dependent upon the architecture of the original biota and the type of CaCO3 used to build the skeletal elements of the organism, e.g. molluscs such as large robust gastropods (e.g. Turbo: figure 11a) will be resistant to physical erosion for a long period of time, as will bryozoans such as the fenestrate Iodictyum (figure 11b), not diminishing in size until diagenesis alters the former but not the latter (see below), whereas a large colony of an articulated zooidal cheilostome bryozoan (figure 11c) will rapidly disintegrate into hundreds of individual zooids following the death of the colony, whereas encrusting bryozoans (figure 11d) will become thin flakes and calcareous algae (Figure 11e) will become small rods. Consequently, carbonate grains tend to be angular to sub-angular, rarely rounded.

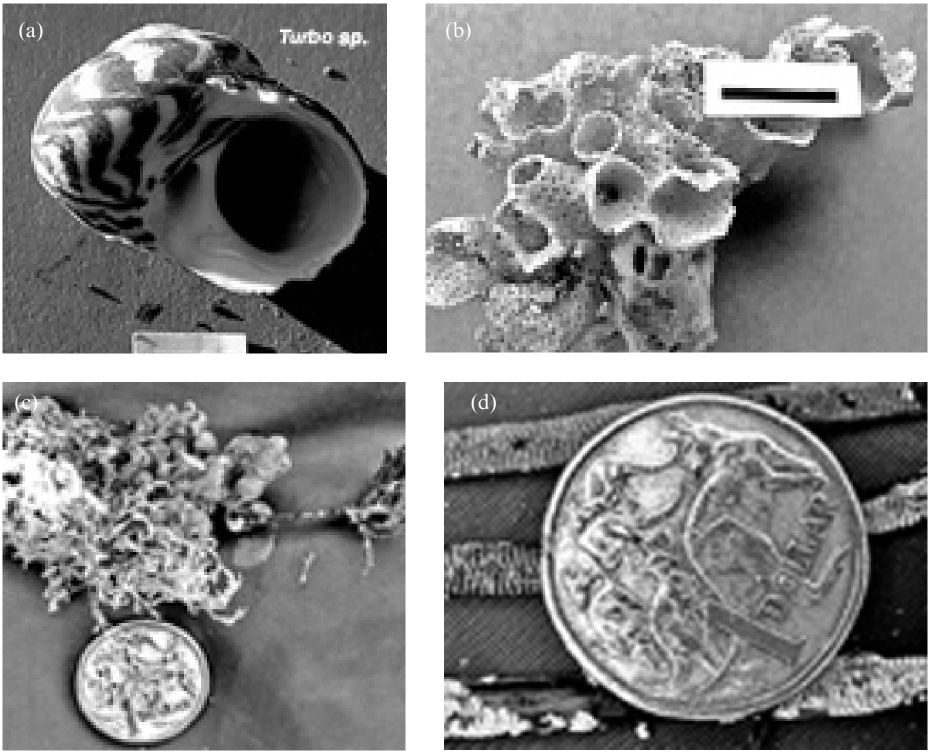

Fig. 11. (a) Gastropods, such as Turbo sp., seen here, live in high-energy surf zones, are thick-shelled and low-spired, and construct their tough calcareous shell with the aragonitic form of $CaCO3$ rather than with structurally weaker calcite. Subsequently, they resist physical weathering. It is, however, readily susceptible to chemical weathering.

(b) Numerous other bryozoans occur on sea-grasses, e.g. the cyclamen-coloured fenestrate Iodyctium phoenicium, which originally gave the incorrect common name of "lace coral" to the phylum, is often found in the area. Much larger, it is preserved as gravel-sized IMC grains.

(c) Directly above the coin, three delicate, recently living colonies of articulated zooidal bryozoans are attached to the stem of the sea-grass Amphibolis sp. Each appears as one "grain", but following the decay of the organic joints between individual zooids, each will disintegrate into dozens of individual fine-grained, easily shattered pieces <0.15 mm in length. These consist of low-Mg calcite, which is chemically stable, so they will persist in the sediment. The dilemma is what is counted?

(d) The encrusting epiphytic bryozoan Thairopora sp. is common on Posidonia sp. blades. Its frontal wall is very thin so that it does not seem to hamper photosynthesis by the grass. When the grass blades are shed and washed ashore, the bryozoans come too! They soon die, and once the seagrass decays, they remain on the beach as fine IMC carbonate grains.

(e) This bleached articulated coralline alga plant is architecturally similar to the bryozoans in (c), and it too will break into dozens of small pieces at each nodal point. It uses HMC in its cell walls, so it will neomorphose into a new mineral over time. This usually has a rounding effect on the fragments. Scale in 2 cm increments.

However, physical weathering is only one of the processes that cause diminution of the carbonate biofragments. Chemical weathering is also equally destructive, and its activity is dependent upon the mineralogy of the biota.

There are four polymorphs of CaCO3 that are used by the calcareous benthic invertebrates to construct their hard parts – namely the orthorhombic mineral aragonite or one of the three trigonal calcite minerals: high Mg-calcite (HMC) with >12 mol % Mg in the calcite lattice, intermediate Mg-calcite (IMC) with 4–12 mol % Mg and low Mg-calcite (LMC) with <4 mol % Mg (BONE & JAMES, 1997). Aragonite is metastable and readily dissolves in cooler water, especially if it is undersaturated with respect to bicarbonate (i.e. low pH) whereas the other metastable carbonate, HMC, neomorphoses into either IMC or LMC, releasing Mg ions into the system. The other two carbonate species used are IMC and LMC, with the former slightly metastable and the latter stable. This is important in the long-term preservation and style of the carbonate sediments, with early marine cements forming in cool-water environments such as the Adelaide coastal area, from the release of the HCO32- into the system from such biota as aragonitic gastropods (JAMES and BONE, 1989; JAMES et al., 2005). Bryozoans and brachiopods are represented in comparable older sediments at a higher rate than they occur in the living biota due to this mineralogical stability, as they use mineralogically stable IMC and/or LMC. Thus, the ongoing destruction of coastal sea-grass meadows by anthropogenic activities (SHEPHERD et al., 2008) is causing the natural cycle of preservation to alter as the habitat is either damaged, thus diminishing its baffling effect or there is complete removal or retreat seawards of the meadows. Calcareous epiphytes are particularly vulnerable to this loss of sea-grass meadows (JAMES et al., 2009), and consequently the passive transport of this biota to the beach no longer occurs, and large banks of dead “seaweed” (figure 12) are no longer commonplace.

The limestone cliffs abutting Zone 4 also contribute a mixed range of grain sizes to the sediments (figure 3d). These cliffs range from mid-Eocene to Recent in age, with their composition reflecting the environment in which the production of their component carbonate grains and the subsequent lithification and diagenesis of those grains, occurred (JAMES and BONE, 2008). In contrast, Zone 1 sediments in the northern mangroves, salt marshes and cheniers are frequently re-worked by high tides flooding inland via the tidal inlets (figure 13; SHEPHERD et al., 2008).

The diversity of the calcareous biota, both infaunal and epifaunal, in the Adelaide coastal area is high. Concomitantly, the distribution of this biota is also high for most taxa. Co-existing communities, including the red coralline algae, both articulated and encrusting types, have a wide range of sizes in their skeletal elements, so that there is an inherent likelihood of this variability in grain size persisting throughout the formation of these autochthonous calcareous grains. Thus, there is no logical rationale for performing tests of skewness and kurtosis on such sediments.

Fig. 12. Large beds of sea-grass were common on the foreshore beaches of Adelaide, until new sewage treatment plants started discharging the treated waste into the sea, from the latter part of the last century. The high N concentration is the main cause of the destruction of the shallow sea-grass meadows, so that banks of washed-up sea-grass now appear only after severe storms. This site is at Glenelg, transect 2 m.

Fig. 13. The S.A. Royal Yacht Squadron marina is alongside the main Adelaide shipping lane. There is a constant build of silt in the basin, but anything larger is quickly picked over by sea-birds. Dredging occurs periodically, with the spoil dumped "offshore", with little regulation.

Grain size – siliciclastic grains

Quartz dominates the allochthonous grains, especially in the fine to medium size fractions (figure 14a), with only 5% in very fine or coarse fractions. This is due to their original terrestrial source, where they are often already fairly uniform in size, e.g. the fine-grained Precambrian Aldgate Sandstone is weathered in the Adelaide Hills, and then transported many tens of kilometres down the Onkaparinga River drainage system. During this transportation phase, which itself may be episodic, physical erosion continues to abrade the chemically-resistant grains, eventually to a relatively uniform size. Flood events cause the debouchment of a gravel/cobble bedload of an atypical size, which then become an anomalous beach deposit, e.g. transect 4-u, north of the mouth of the Onkaparinga River (figure 14b).

In contrast, the siliciclastic rocks of slightly younger age that form the rocky beach and shore platform at Marino Rocks are weathered to produce smaller "grains", but these have not been transported long distances, and hence it is only the smaller grains that become rounded, with the larger cobbles often having a flat, smooth upper surface due to abrasion by the diurnal action of tidal flow. These cobbles are frequently overturned during storm events so that the obverse side then becomes smoothly planed off, resulting in strandlines of oblate cobbles. Similar cobble beaches are produced at locations like Sellicks Beach by the gullying of nearby slopes of ancient outwash fans. Outwash fans contain a bimodal distribution of rounded or oblate pebbles in a fine clay/quartz matrix so the cobbles are not carried out to sea, but remain in the supratidal area, where they form long linear strandlines (figure 14c). The fine matrix, however, is transported offshore.

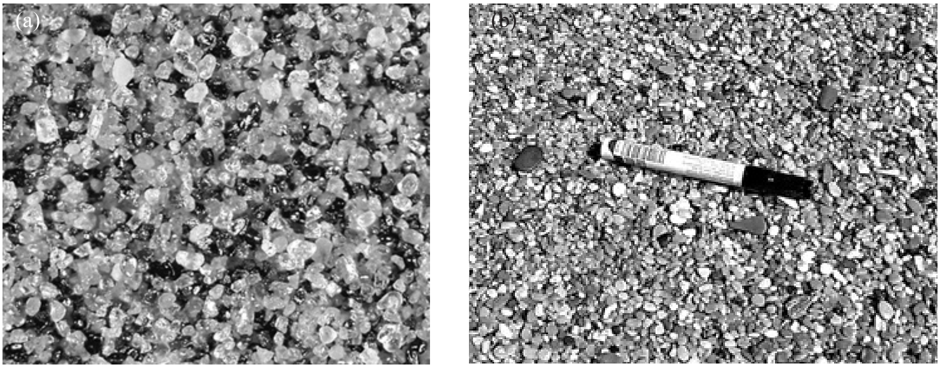

Fig. 14. (a) Sample from ACWS 4-z.1(x25), showing heavy minerals (dark grains), particularly garnets, derived from Permian erratics and tills. Like all placers, the heavy minerals co-settle with quartz grains more than double their size, due to gravity differences.
(b) Well-polished, oblate river gravels deposited on to the beach by the Onkaparinga River during times of high flow, have been transported many tens of kilometres downstream from the Aldgate Sandstone in the upper reaches of the Adelaide Hills. The fine black grains are ilmenite, from the same source. Wave action in the lower reaches of the river estuary results in accumulations of these as heavy mineral placer deposits, but they are economically insignificant.

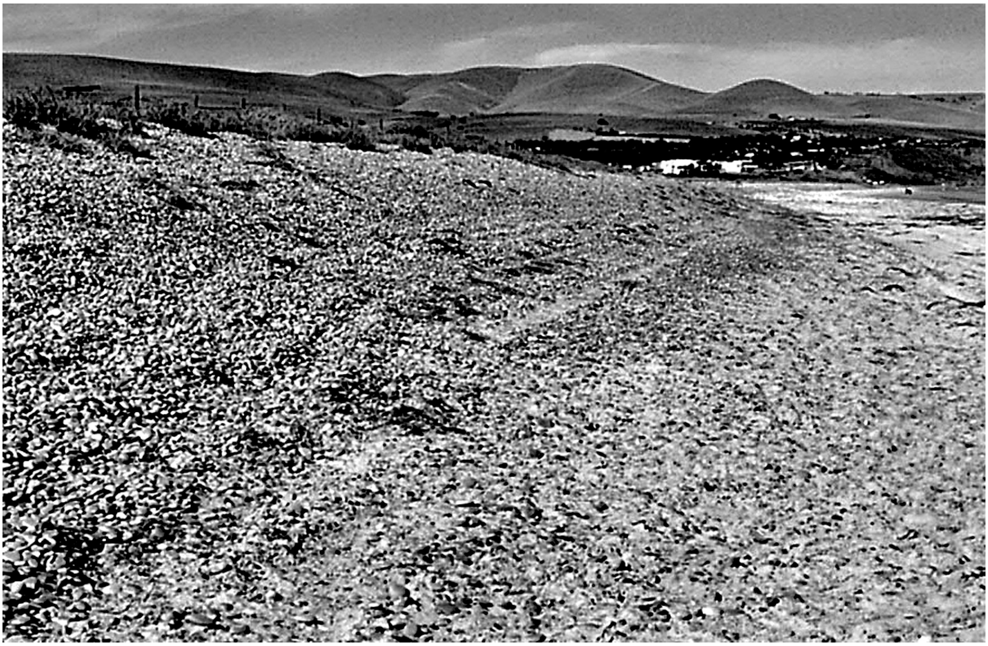

Fig. 14. (c) Weight-sorted shingles of Precambrian ABC Quartzite derived from the outwash fans that form outwash aprons on the bases of the rounded Cambrian hills on the skyline. Thrust faulting has juxtaposed the quartzite to higher geomorphic levels, with the older Precambrian on the RHS, with Cambrian limestones and siltstones forming the lower, rounded hills.

Other grains that contribute to the size spectrum include minor occurrences of minerals that have weathered out of Permian glacial till, such as garnets, ilmentite and staurolite (figure 14a). These are particularly noticeable along transect 4-z.

Clays are commonly debouched from all the creeks and rivers that have their outlets on to the beach, as they traverse the Adelaide flood plain (figure 14d), with many of them also having their headwaters in the Adelaide Hills. After heavy rains, the major outlets have plumes of red-brown silt colouring the water for up to 2 km seawards. There is little attempt to control the flow of stormwater from the metropolitan area into the sea. Indeed, in addition to the natural creeks, dozens of stormwater drains have been purpose built to flow on to the beaches. These are the main source of anthropogenic material on to the sea floor, with cigarette butts the numerically highest "grain". Marinas are also sites of deposition of fine silts and mud, partially due to the continual churning up of the water by boat engines coming and going.

Fig. 14. (d) Outlet of Willunga Creek which traverses mainly agricultural land, so is not a major polluting contributor. A firm, quartz-dominated sandy beach fronts the highly indurated Tertiary limestones, which are topped with Pleistocene friable silts, clays and calcrete. The rounded quartzite pebbles on the sand have been carried northwards from Precambrian quartzites, (see figure 14c).

Statistical interpretation

Tables 2 and 3 give the exact percentages of the different grain sizes present in the sample from each of the 295 sites. There are many different methods of statistically presenting this data, including contour maps and pie diagrams (figure 15) but it is considered that distribution maps are the best method to show immediately the entire study area. There is still, nevertheless, the dilemma of choosing bin sizes. The traditional classification of bin sizes has been applied but other divisions are possible, using the data provided in the tables.

Seasonal variability

Distribution maps show that there is no significant seasonal difference, even though grain-size heterogeneity is present throughout the area. The pie diagrams also depict this particularly well, but space limits their presentation (data available electronically, if required, from corresponding author).

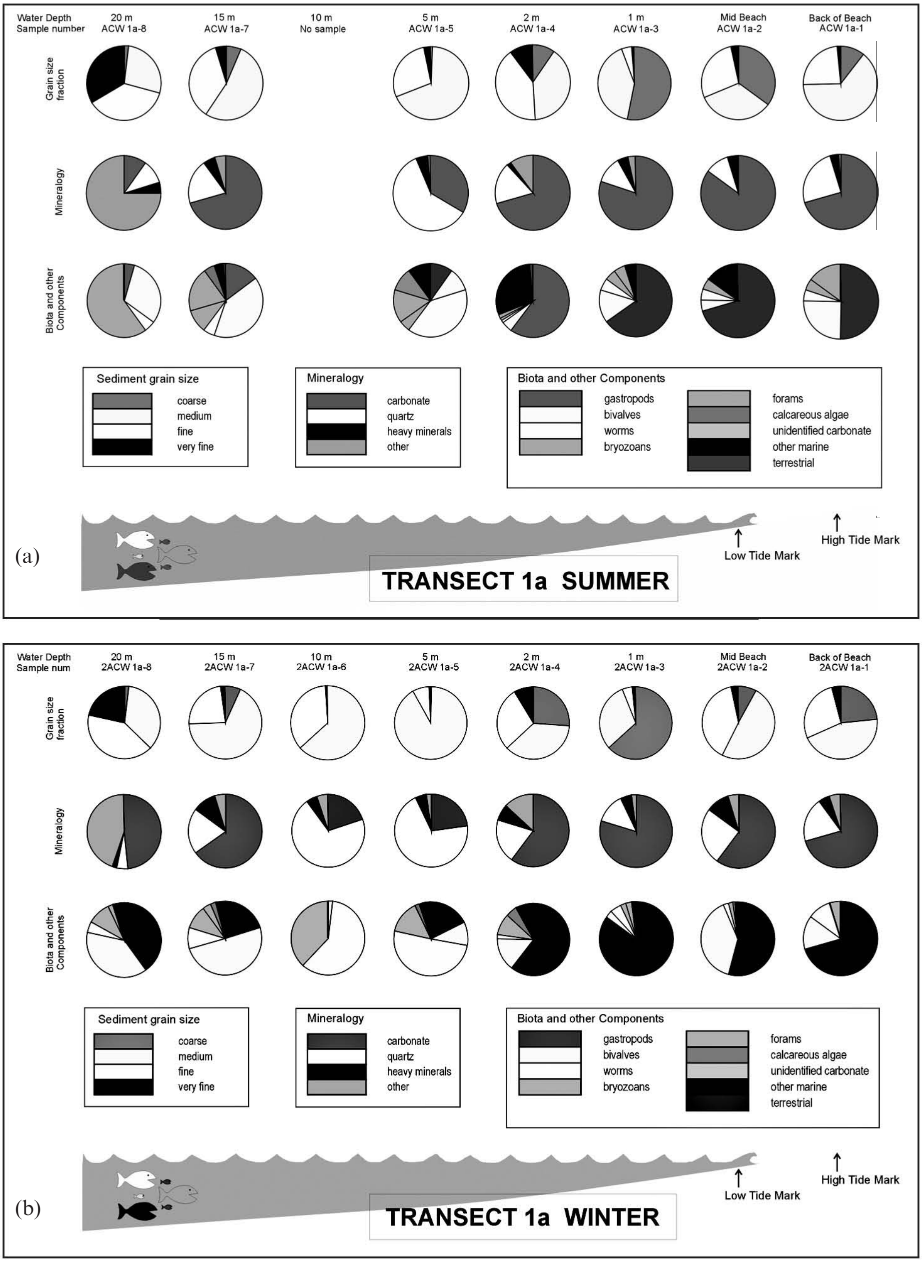

Fig. 15. Pie charts showing, along the top line, the distribution of grain size at each of the sites along Transect ACWS 1-a during (a) Summer, and (b) Winter. These charts constrain the viewer to a narrow window. The middle and lower lines depict other parameters, allowing an overall view of the environment.

Management strategies for urban coasts

Any management planning in temperate environment urban coastal areas has to consider this maxim – they are dealing with mixed sediments that contain two main populations of grains with vastly different physical and chemical characteristics. It is mandatory to shed the often held opinion that "sand consists of grains of quartz". The medium size fraction, particularly, reflects the influence of the aforementioned two populations, with the quartz fraction tending to be concentrated inshore and the carbonate fraction in the offshore regions. Invariably there are exceptions, e.g. the muddy flats of the northern region, where the environment is favourable for huge populations of smaller molluscs. This is not a "new" scenario, as evidenced by the extensive shell-grit cheniers that blanket the low-lying adjacent area. Similarly, the wide intertidal area of the Semaphore–Largs Bay area, the depocentre of the finer fraction resulting from long-shore drift, is a favourable environment for foraminifers, which then contribute their fine to very fine-sized tests to the sediment budget. This latter area is the target for future sources of sand to replenish the southern metropolitan beaches in the Marino Rocks area. The foraminifer tests are fragile and unlikely to survive transport, by either truck or via a pipe as a slurry mix. On the other hand, this will result in the material that is "imported" by longshore drift being quickly sent back to whence it came! But, the alkalinity will be quite different to the original state, and so the local biota will either have to adapt, or die out, or be replaced by a new biota assemblage. The local biota, hopefully, has as one of its major components, sea-grass meadows, and even though the sea-grass itself does not become a component of the sediment, it does act as the substrate for a volumetrically-large assemblage of calcareous epiphytes (JAMES et al., 2009).

So, the strategies needed include better replenishment scenarios, alternative drainage areas on the Adelaide coastal plain for stormwater, reduction of chemical pollutants from industry, particularly in the northern area, and an overall education of the general public as to the fragility of the ecosystem of their "coast" (SHEPHERD et al., 2008).

CONCLUSIONS

The sediments veneering the sea floor in the coastal area of Adelaide are markedly heterogeneous. This applies particularly to the grain size of the sediments. There is no single factor that causes this heterogeneity, but rather it is a complex web of interacting processes such as hydrodynamics, climate, appropriate nutrient and photic levels and vigour of the sea-grass beds, which have a binding/baffling effect on the sediment grains, particularly when the sea-grass is in a healthy state. The intrusion of anthropogenic activity, e.g. all types of boat and human activity, particularly in the intertidal zone, and structures, particularly those that impede the natural movement of sediment grains, e.g. the marinas at O'Sullivans Beach, Glenelg and North Haven, has disturbed this natural cycle. Major changes to the natural drainage pattern and the geomorphology of the coastal area, particularly the beachfront buildings, roads and seawalls, have led to episodic debouchment of sediment grains on to the beach and intertidal area, often catastrophically, rather than the historical gentle ongoing flow. Management of this last point is urgent. Most of Adelaide's sewage and stormwater is emptied into the sea. The general public needs to realise that the sea is not a forgiving rubbish dump, and insist that alternatives are implemented.

The heterogeneity of the sea-floor sediments, especially in terms of grain size, has been the case for at least the last 125 Ka. The ratios, however, are changing over smaller lateral distances and water depths, since the settlement of Adelaide in the 1800s, at an increasing rate to the present day. In contrast to the plethora of pristine beaches abutting the South Australian coastline, Adelaide's beautiful beaches are under threat and will disappear unless ongoing scientifically-devised monitoring is employed and better management practices, based on scientific fact, are instituted urgently. Coastal areas are the natural cyclic product of physical, chemical and biological processes – break these cycles, and the resulting end product changes for better or worse. The latter has been the case in the Adelaide coastal environment.

The following points drive the natural cycle and produce beaches:

- Sediment grains on the sea floor of the Adelaide coastal area are heterogeneous in terms of grain size.
- Seasonal variation in grain-size heterogeneity is minor.
- Grain size reduction is a result of ongoing weathering, physical, chemical and biological.
- Mineralogy is the major cause for differences in weathering results.
- Grain shape is forced by the origin of the grains – biogenic (angular) or terrigenous (rounded).
- Terrigenous sources supply the siliciclastic grains, i.e. >90% of quartz grains are allochthonous.
- The marine environment is the source of the carbonate grains, i.e. >90% of carbonate grains are autochthonous, produced by benthic invertebrates.
- Benthic invertebrates use four different carbonate minerals that are polymorphs – aragonite, high Mg-calcite (HMC), intermediate Mg-calcite (IMC) or low Mg-calcite (LMC).
- The chemical composition of benthic invertebrates using LMC for their skeletal elements remains unchanged throughout geological time.
- Stormwater drains debouching on to the beach are the major anthropogenic pollution source on the Adelaide beaches.
- Loss of sea-grass meadows from the shallows is a major cause of increased erosion of the sea floor.
- Longshore drift transports finer grains northwards, until shallowing results in deposition.
- Winnowing of sediments occurs in artificially-deepened inshore waters, partially as a result of longshore drift.
- Beach replenishment needs to mimic the natural cycle.

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