Journal of Coastal Research	15	2	537–553	Royal Palm Beach, Florida	Spring 1999

Beach Sediments of Crete: Texture, Composition, Roundness, Source and Transport*

Mauri Pyökäri

Department of Geography
University of Turku
Turku, Finland SF-20500

ABSTRACT

PYÖKÄRI, M., 1999. Beach Sediments of Crete: Texture, Composition, Roundness, Source and Transport. *Journal of Coastal Research,* 15(2), 537–553. Royal Palm Beach (Florida), ISSN 0749-0208.

The texture, composition, provenance, and transport of beach sediments and the roundness of sediment grains were studied on 22 beaches on the coasts of Crete in southern Greece.

The studied beaches range from low-carbonate to high-carbonate beaches, where the texture and mineral composition of beach sediments and roundness of sediment grains display some degree of local variation. Beach sediments consist mainly of medium and coarse sand, being moderately well or well-sorted, symmetrical or negatively skewed and mesokurtic or leptokurtic. On beaches where no rivers enter the sea the mineral composition is closely related to nearby exposed coastal formations (sea cliffs, bluffs and rocks), the grain-size frequency distribution of beach sediments being nearly normal, and the roundness of sediment grains rather good. Where rivers discharge on to the beach or near to it, the mineral content of these beaches is related both to the coastal formations and the formations situated inland in the catchment basins of the rivers. Coastal abrasion and fluvial sediments on shores are mixed by waves and littoral drift, causing somewhat poorer sorting and roundness. Low-Mg calcite and quartz are the most common minerals (altogether 50–90%) in the beach sediments on Crete. The other common minerals are dolomite, feldspars, epidotes, pyroxenes, amphiboles, tourmaline, zircon, titanite and magnetite; the sources being mainly dolomites, phyllite-quartzites, ophiolites, flysch, and sandstones on the mountains and coasts of Crete.

The direction of net littoral drift is determined mainly by the predominant wind and waves approaching from the direction of the greatest fetch, while the onshore winds and waves (the directions of the fetches arranged according to the length of the fetch) greatly determine the direction of seasonal littoral drift. These two wind factors together determine, to the large extent, the direction of seasonal littoral drift in the surf zone, whereas in the swash zone the direction is determined only by the onshore winds and waves. On the other hand, the prevailing wind and waves have a little effect on the direction of sediment movement on the coasts of Crete.

ADDITIONAL INDEX WORDS: *Beach sediments, texture, composition, roundness, provenance, littoral drift, fetch, predominant and prevailing waves, Crete, Greece.*

INTRODUCTION

Crete is the largest island of the Hellenic Arc, a convergent zone between Greece and Turkey associated with northward subduction of the African plate under the Aegean (LORT, 1977; HALL *et al.,* 1984; VANNEY and GENNESEAUX, 1985). The island is situated in the centre of the arc (Figure 1), but its elongation parallel to the arc is not due to convergence but to late Cenozoic regional extension. Crete is a Tertiary nappe pile deposited on continental crust with little clear evidence that a collision actually piled up the nappes (HALL *et al.,* 1984; ROBERTSON and DIXON, 1984). At the beginning of late Miocene time, Crete transformed into a mosaic of relatively small-sized horst blocks separated by grabens filled by Neogene and Recent sedimentary rocks (HALL *et al.,* 1984; MEULENKAMP, 1985). The Cretean Basin, in a back-arc setting, consists of an elongated depression from west to east (Figure 1). These basins and ridges extend shoreward by a system of U-shaped graben-bays and horst-promontories (Figures 1 and 2) (VANNEY and GENNESEAUX, 1985). South of Crete is situated the Hellenic Trough, a presently active subduction zone comprising a series of depressions, the deepest of which (over 5000 m) lies to the southeast of Crete.

There have been a large number of geological studies dealing with the lithology, stratigraphy and sedimentology of the formations of Crete (*e.g.,* HALL *et al.,* 1984; HEMPEL, 1984) and two studies of shoreline changes (PIRAZZOLI *et al.,* 1982; POSTMA and NEMEC, 1990). Nothing has hitherto been published on beach sediments and how shore processes have affected this material. The purpose of this paper is to throw light upon that what has happened on the shores of Crete. This work also forms a part of geographical studies carried out by the author on the coasts of the Eastern Mediterranean Sea in 1982–1996 (*e.g.,* PYÖKÄRI and LEHTOVAARA, 1993; PYÖKÄRI and YLI-KYYNY, 1995).

Winds and Waves around Crete

In the sea around Crete, summer winds called Etesians or Meltemi are mainly NW, but N and W winds are also common (Figure 2). They are light to moderate, rarely rising to gale force, and remarkable steady in direction. Cyclonic winter winds, more variable in direction, are generally also NW

97068 received and accepted in revision 29 April 1998.
* To the memory of my late wife Maire Pyökäri.

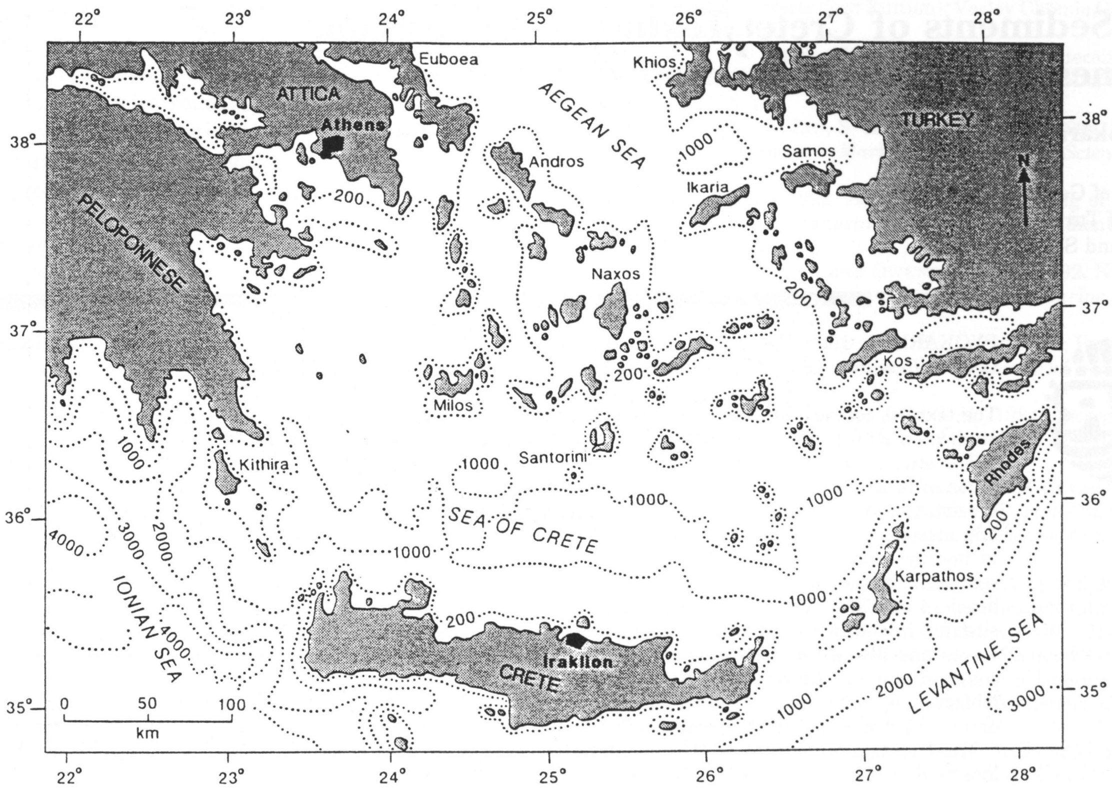

Figure 1. Map of the Sea of Crete, showing the study area, the island of Crete, discussed in text.

with a secondary W mode, but N, NW, and SW winds are not uncommon (KENDREW, 1953; MARKGRAF, 1961). They are moderate to strong and occasionally of gale force. The approach of prevailing waves (the most common wind and wave direction) is from WNW to NNW, while predominant waves (the most effective influence on any particular stretch of coast due to fetch) reach the northern coast mainly from N to NE, the eastern coast from ESE to SSE, the southern coast from WSW or SE, and the western coast from WSW to WNW. Maximum tidal range is about 0.3 m (ISTITUTO IDROGRAFICO DELLA MARINA, 1981), but stormy winds can cause a rise in sea level more than 1 m (POSTMA and NEMEC, 1990), as also indicated by the relative position of storm berms on the beaches studied.

Physiographical Setting of the Study Area

The inland of Crete, whose coasts were studied, is dominated by plateaux and mountain ranges with peaks 800–2450 m in height, the major axes trending W–E. Several short rivers run from the mountains down to the coast and form there small coastal plains, the widest on the N coast. The N and E coasts consist of emerged horst blocks of limestones, dolomites, phyllites and quartzites usually with high cliffs and of depressions between horsts with fluvio-lacustrine to lagoonal or marine sediments, marls, flysch and sandstones (CREUTZBURG *et al.,* 1977) (Figure 2). North of the Idha Mountains there are ultramafic rocks (mostly serpentinized peridotites) and west of Sitia town in the phyllite-quartzite series mafic volcanites (diabase, pillow lava, spilite, metabasalt and andesite) (PAPASTAMATIOU *et al.,* 1959; CREUTZBURG *et al.,* 1977). The size and profile of the beaches vary from small sand-gravel pocket beaches at the base of a cliff (*e.g.,* Beach P) to several-km-long beaches with a well-developed berm and backshore with a bluff (*e.g.,* Beach C) or dunes (*e.g.,* Beach I).

The S and W coasts are more rocky and cliffed than the N and E coasts; particularly the cliffs formed in coastal horst mountains on the S coast in the western part of Crete are impressive. The horsts consist of limestones and dolomites (locally associated with coarse breccias), phyllite-quartzites, and west of the Asterousia Mountains ophiolites (mainly serpentinized peridotites, subordinate gabbros and basalts). There are also ultramafic rocks (peridotites) south and southwest of the Idha Mountains. Depressions between horsts are made up of thick sequences of marl deposits, flysch, sandstones and weakly cemented fluviolacustrine, lagoonal or marine sediments (CREUTZBURG *et al.,* 1977). Beaches vary from the 3-km-long Beach S with a well-developed backshore to very wide beaches with dunes (*e.g.,* Beach A) or small pocket beaches behind of which is a steep slope of debris material (*e.g.,* Beach T).

Beaches Sampled

Twenty-two different types of beaches were selected, on the basis of situation (horst or filled grabens), configuration

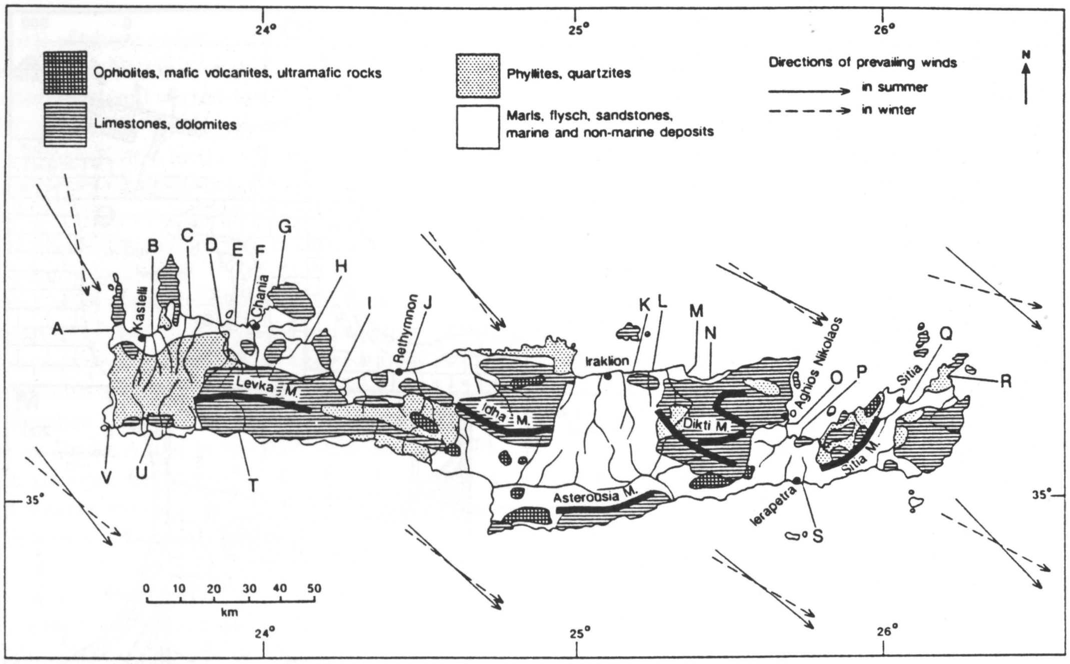

Figure 2. Locations of beaches A–V studied on the coasts of Crete. Nearly straight beaches (0.5–3 km): (A) Falasarna Beach, (E) Aghia Marina Beach, (H) Kalives Beach, (L) Gouves Beach, (N) Malia Beach, (Q) Sitia Beach, (S) Ierapetra Beach, (U) Paleochora Beach, (V) Elafonisi Beach. Straight beaches (4–8 km): (B) Kastelli Beach, (C) Kolimvari Beach, (D) Platanias Beach, (I) Georgioupolis Beach, (J) Rethymnon Beach. Pocket beaches: (F) Kalamaki Beach, (G) Stavros Beach, (K) Amnissos Beach, (M) Hersonissos Beach, (O) Almiros Beach, (P) Istro Beach, (R) Vai Beach, (T) Aghia Roumeli Beach.

(pocket beach or nearly straight beach), profile (cliff, bluff or dunes), whether a river (rivers) runs on to the beach or not, and the length of the fetches in the directions of prevailing or predominant waves, as key areas for study of the texture, mineral composition, provenance and transport of beach sediments (Figure 2, Beaches A–V). The sampling sites are presented in Figure 3 and measured shore indicators from the beaches studied in Table 1.

METHODS

Surface samples were collected during June–July 1990 in the western part of Crete and during July 1992 in the eastern part of Crete. Both times the weather was typical of the Mediterranean summer (Markgraf, 1961). Sediment samples were gathered along every survey line on Beaches A–V (Figure 3), three from the surf zone at depths of 0.5 m, 1 m, and 1.5 m, three from the swash zone on the foreshore and three from the beach above the swash zone on the backshore. Grain-size distributions were measured with standard sieves at ¼ ϕ intervals. Cumulative log-normal plots of sediment weights were used to compute the textural parameters using Folk's (1966) graphic method.

The mineral and lithic-fragment compositions of beach sediments and roundness of sediment particles (Powers, 1953) were studied at each location using a multiple split of the combined grain samples. The split was made by halving combined beach samples of a shore at random with a sediment divider a sufficient number of times so that the sample obtained was representative for each section of the beach. The roundness of the grains was determined visually avoiding the influence of grain size in the determination of the roundness class. The sand was studied under a polarising microscope to determine the mineralogical composition. The lithic fragments were also compared with some identified rock samples gathered from Crete. The carbonate minerals and feldspars were determined by staining and etching techniques (Friedman, 1959; Allman and Lawrence, 1972; Pyökäri and Lehtovaara, 1990) combined with a microscopic study. Proportions of carbonates and non-carbonates were also calculated by dissolution representative samples in 0.5 N hydrochloric acid. The proportions were very similar to those obtained by microscope, indicating that the results are reliable.

Variation in the textural parameters of samples (McLaren and Bowles, 1985; Pyökäri and Lehtovaara, 1987), the direction of sand bed-load movement in the surf and swash zones, floating bottles on the surface, and bubble trains were used to determine the direction of seasonal littoral drift (beach drift and longshore drift) during the study period. Some geomorphic indicators (*e.g.,* long and massive structures interrupting littoral drift, beach width and beach slope, stream mouth diversions) and beach-sediment composition were used to determine the direction of net littoral drift (*cf.* Taggart and Schwartz, 1988; Pyökäri and Lehtovaara, 1993).

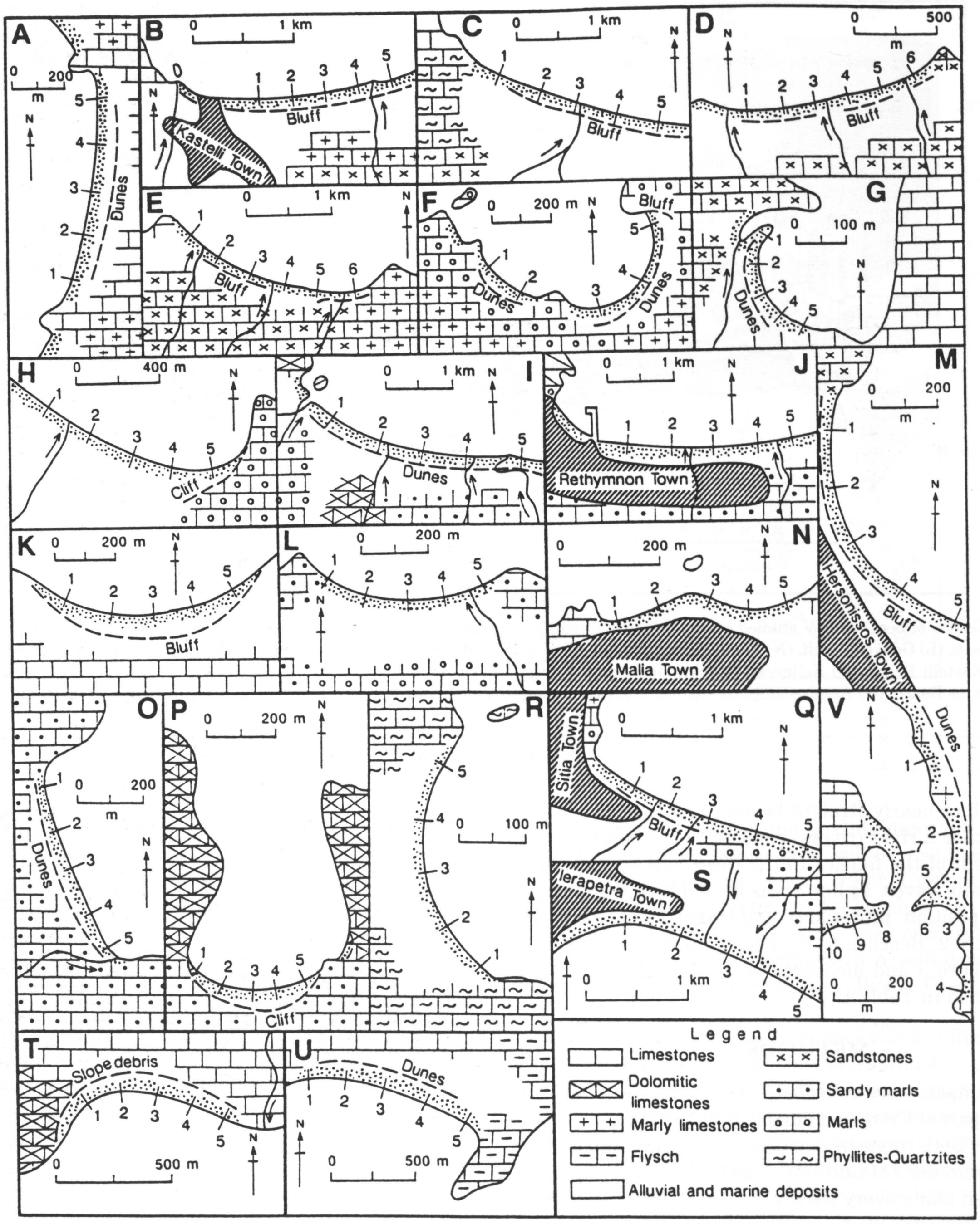

Figure 3. Sampling sites A–V are the same beaches on Crete as in Figure 2. The numbered lines on the beaches show the sites of surveyed beach profiles and places where sediment samples were taken from three shore zones. Beaches are stippled.

RESULTS

Textural Characteristics of Beach Sediments

On the beaches of Crete the beach-sediment size is highly variable, ranging from very fine sand to pebbles, with medium and coarse sand most common. Pebbles and granules are common on Beaches Q, T, P, R and M and in the swash zone on Beach C, and fine sand on several beaches studied. The mean grain size (M_z) of beach sediment is coarsest on Beaches Q and T and finest on Beach O (Table 2). The mean grain size is coarsest in the surf zone on Beaches Q and T and in the swash zone on Beach C, and finest in the surf zone on Beaches O, C and F and in the beach and swash zones on Beach O. In general, the mean grain size is rather coarse, but it may be fine or very coarse in surf-zone sediments (Table 2).

The sorting (σ_I) of shore sediments varies from very well sorted (Beaches K and N) via well-sorted (Beaches O, E, F and I) and moderately well sorted (most beaches) to poorly sorted (Beach T) (Table 2). Sorting is best in the swash and beach zones on Beach K and in the swash zone on Beach E, and poorest in the surf zones on Beaches L, S and T. Sorting is generally best in swash-zone sediments and poorest in surf-zone sediments, where the poor sorting is caused by the poorly-sorted tail of coarse material.

Skewness (Sk_I) shows nearly-symmetrical or negatively-skewed distributions (Table 2). The mean values for the different shore zones, however, reveal that the sediment distributions are sometimes strongly negatively skewed (*e.g.* in the surf zones on Beaches C and F) or positively skewed (*e.g.* in the beach zone on Beach A and in the surf zone on Beach T). Skewness is, in general, negatively skewed in the surf-zone sediments and nearly symmetrical in the beach-zone and swash-zone sediments. The mean values for kurtosis (K_G) are mesokurtic or leptokurtic, except on Beach K, where it is platykurtic, and Beach O, where it is very leptokurtic (Table 2). The mean values for the different shore zones vary more. The swash-zone sediments are meso- or leptokurtic, as is the beach-zone sediment generally too, but the surf-zone sediments vary from platykurtic to very leptokurtic.

Composition of Beach Sediments

The bulk of sediments was revealed to be carbonates (62–90%) on Beaches A, G, K, T and V, the carbonate minerals also representing the most frequent group on Beaches E, L, M, N and O (Figure 4) (*cf.* SACCANI, 1987). The proportion of carbonates varies from 8.5% to 90%, being smallest on Beach C and greatest on Beach G. Low-Mg calcite is by far the most abundant mineral species in this group (5–77%), the proportion of high-Mg calcite and aragonite being low (1–14%); the largest proportion occurs on Beaches G and V. The proportion of dolomite and magnesite varies from 0.5% to 11.5% with dolomite more frequent than magnesite, the largest proportion being on Beaches S and T.

The non-carbonate minerals are characterized by minerals of the silica group (mainly quartz, somewhat chert) except on Beaches M, P and R, the proportion varying from 7% (Beach G) to 76% (Beach C) (Figure 4) (*cf.* SACCANI, 1987). The proportion of silica minerals is most frequent of all the mineral groups on Beaches B–D, F, H–J, Q, S and U. The sediments of Beaches C and D are exclusively dominated by quartz (76% and 61% respectively), while chert is the most abundant non-carbonate mineral in the sediments on Beach T (32.5%), being also common on Beaches U and S (5.8% and 4.5% respectively) on the southern coast. The proportion of minerals of the feldspar group (mainly plagioclase) vary from 0.3% (Beach V) to 31% (Beach P). It represents the most common mineral group on Beaches P and R and the most common non-carbonate mineral group on Beach M.

The mineral suites of the beach sands also consist of fair amounts of mafic minerals (0.1–19%), pyroxenes, amphiboles (*e.g.,* hornblende and actinolite-tremolite) and tourmaline being most frequent among the minerals of this group (Figure 4). The proportion is greatest on Beaches P and M (19% and 14% respectively), which are characterized by pyroxenes and hornblende. Fair amounts of the minerals of the epidote group occur on some beaches, the proportion being greatest in the sediments of Beaches L, Q, R and S (13–22%). There are also small amounts of accessory minerals represented by such species as garnets, titanite, zircon, spinels (mainly magnetite) and apatite. Titanite is a common mineral on Beaches L, Q and S (4–4.5%), zircon on Beaches C and D (3–5.5%) and apatite on Beach R (2.4%), while spinels are frequent on Beaches M and L (2.5–3.3%) and garnets on Beaches M and S (2.5–3%). These same mafic, epidote and accessory minerals also occur in the heavy mineral study of MEZZARDI and SACCANI (1989) made from the sediments on nearly the same beaches. The proportion of lithic fragments on some beaches varies from 0.1% to 15.5%, being most abundant on Beaches M and R (15.5% and 14% respectively). Marl, sandstone and phyllite-quartzite fragments are most common with limestone-dolomite particles making up the rest.

When the frequency distributions of the mineral and lithic-fragment contents of the beach sediments (Figure 4) were tested against each other by the Kolmogorov-Smirnov test they differed, in general, significantly because of different sediment supplies. The beaches which did not show any significant differences from each other would seem to have nearly similar source rocks (*e.g.,* Beaches A, G and V or Beaches N and O) (CREUTZBURG *et al.,* 1977).

Roundness of Sediment Grains

The roundness of sediment grains on the beaches varies from very angular to well-rounded (Figure 5). The roundness of all grains is best on Beach A and good on Beaches E, K, M, N and T (sub-rounded grains commonest) probably being due to a great carbonate proportion in beach sand and poorest on Beach P and poor on Beaches B–D, J, L and U (angular grains commonest), which are non-carbonate beaches. The roundness of carbonate particles is much better (sub-rounded grains commonest on the beaches except on Beaches F, G and V) than that of non-carbonate clasts, probably because they are softer minerals than most of the non-carbonates. The most rounded carbonate grains are found on Beach J (sub-rounded and rounded grains commonest); the roundness is also good on Beaches B, D, I, M, P and U (proportion of rounded grains 18–35%). The poorest roundness of carbonate clasts is in the sediments of Beach G.

The roundness of non-carbonate clasts is rather poor, grains being typically sub-angular or angular. The non-carbonate clasts on Beach G exhibit the highest degree of roundness (sub-rounded grains commonest), higher than the carbonate clasts on this beach. The roundness is also rather good on Beaches H, M, N and Q–T (sub-angular grains commonest), poorest on Beach V (proportion of very angular grains 30%) and rather poor on Beaches A–E and L (proportion of very angular grains 10–17%).

The Kolmogorov-Smirnov test showed that the frequency distributions for the roundness of all sediment grains (Figure 5) on the beaches studied differed from each other mainly

Table 1. *Situation, types and measured shore indicators characteristic of the beaches studied. Beaches A–V are as in Figure 2.*

Situation Beach Type Length	Backshore Width Formations	Foreshore Width Formations	Inshore Width Formations	Beach Face	River	Fetches Maximum Others
A. Falasarna Beach						
Graben Straight beach, 1 km	40–200 m, dunes 1–3 m	8–12 m, berm	50–70 m, parallel bars	9–14°	none	W SW–WNW
B. Kastelli Beach						
Graben Straight beach, 5 km	10–60 m, bluff 1–2 m	6–10 m, berm, beach ridges	30–80 m, cres- cent bars	6–10°	rivers on the beach	N NNW–N
C. Kolimvari Beach						
Graben Straight beach, 4 km	25–40 m, bluff 1–2 m	10–12 m, berm, beach ridges	8–18 m, parallel bar	6–8°	rivers on the beach	ENE N–ENE
D. Platanias Beach						
Horst Straight beach, 5 km	9–25 m, bluff 0.5–1.5 m	4–7 m, berm	6–40 m, parallel bar	8–12°	rivers on the beach	N N–NE
E. Aghia Marina Beach						
Graben Straight beach, 3 km	8–20 m, bluff 0.5–1 m	6–15 m, berm, beach cusps	40–70 m, parallel bar	5–10°	rivers on the beach	N N–NE NW
F. Kalamaki Beach						
Graben Pocket beach, 0.6 km	10–25 m, bluff 1 m, dunes 1 m	4–6 m, berm	50–70 m, parallel bar	7–16°	none	N N–NE NW
G. Stavros Beach						
Horst Pocket beach, 0.2 km	8–20 m, dunes 0.5–1 m	2–4 m	10–20 m	4–13°	river on the beach	NNE NNE
H. Kalives Beach						
Horst Straight beach, 1 km	10–25 m, cliff 2–5 m	8–12 m, beach cusps	20–40 m, parallel bar	8–12°	river on the beach	NNE NNE–NE
I. Georgioupolis Beach						
Graben Straight beach, 8 km	50–70 m, dunes 0.5–1 m	6–10 m, berm	50–80 m, cres- cent and paral- lel bars	5–10°	rivers on the beach	N N–ENE
J. Rethymnon Beach						
Graben Straight beach, 7 km	20–80 m	5–6 m	10–80 m, cres- cent and swash bars	5–10°	rivers on the beach	NNE NNW–NE
K. Amnissos Beach						
Graben Pocket beach 0.8 km	30–70 m, bluff, 0.5–1.5 m	4–6 m, berm	60–80 m, parallel bars	7–10°	none	NW WNW–NW N–NE
L. Gouves Beach						
Graben Straight beach, 0.5 km	13–35 m	10–12 m, berms	30–40 m, parallel bar	7–8°	river on the beach	WNW NNW–ENE
M. Hersonissos Beach						
Graben Pocket beach, 1 km	7–12 in, bluff 2–4 m	7–12 m	20–40 m	6–7°	none	ENE N–ENE
N. Malia Beach						
Horst Straight beach, 0.6 km	25–50 m	4-6 m, berm	50–80 m, parallel bar	10–12°	none	NW NW–NE
O. Almiros Beach						
Horst Pocket beach, 0.6 km	12–25 m, dunes 0.5–0.8 m	4–5 m	60–80 m, swash bar	10–12°	river on the beach	NE NE–ENE

Table 1. *Continued.*

Situation Beach Type Length	Backshore Width Formations	Foreshore Width Formations	Inshore Width Formations	Beach Face	River	Fetches Maximum Others
P. Istro Beach						
Graben Pocket beach, 0.3 km	5–15 m, cliff 5–20 m	5–12 m, beach ridge	15–30 m	10–17°	none	N NE
Q. Sitia Beach						
Graben Straight beach, 2 km	5–15 m, bluff 1 m	10–15 m	8–10 m	5–6°	rivers on the beach	NNE NNW–NE
R. Vai Beach						
Horst Pocket beach, 0.4 km	15–40 m	3–5 m, berm, beach ridge	20–50 m	10–15°	none	ESE NE–SE
S. Ierapetra Beach						
Graben Straight beach, 3 km	10–30 m	4–6 m	20–30 m	5–10°	rivers on the beach	WSW ESE–WSW
T. Aghia Roumeli Beach						
Horst Pocket beach, 0.7 km	15–40 m, slope debris	7–9 m, berm, beach cusps	8–12 m	8–10°	river near by	WSW SE–WSW
U. Paleochora Beach						
Horst Straight beach, 1 km	25–120 m, dunes 2 m	5–10 m	25–30 m	8–14°	river near by	WSW SSE–WSW
V. Elafonisi Beach						
Horst Straight beach, 1 km	10–70 m, dunes 0.5–3 m	4–6 m	20–180 m, spit bars, crescent bars	4–6°	none	WSW SSE–WSW WNW–NW

significantly due to different sediment supplies and abrasion processes. The beaches which did not show any significant differences from each other would seem to exhibit nearly similar sediment supplies and abrasion processes (*e.g.,* Beaches D and J or Beaches F and O, Figures 4–7). As to the roundness of non-carbonate grains and that of carbonate grains, there were beach sediments which did not differ from each other significantly as also beach sediments which differed from all the beaches highly significantly.

DISCUSSION

The nature of beach sediments on Crete shows rather complex regional patterns which can be related to variations in the adjacent coastal rocks and the rocks of the catchment basins of the rivers discharging on to the coast, to coastal orientation and the combined effects of coastal processes which have transported and reworked these sediments.

Provenance of Beach Sediments

On most of the straight, long beaches, where rivers run on to the beach or nearby (Figure 2, Table 1: Beaches B–E, H–J, and Q), sediments are mostly coarse sand, moderately well sorted, nearly symmetrical and lepto- or mesokurtic, except the surf-zone sediments, which are mainly negatively skewed and leptokurtic (Table 2). Beach sediments consist mainly of minerals of the silica and carbonate groups (Figure 4). The roundness of grains is rather poor (Figure 5), poorest on the beaches where fairly large rivers enter the sea from high mountains, as on Beaches B–D and I–J. All this indicates a constant input of material all along the coast and mostly of rather short transport (*cf.* JACOBSEN and SCHWARTZ, 1981; TAGGART and SCHWARTZ, 1988; PYÖKÄRI and LEHTOVAARA, 1993; PYÖKÄRI, 1997). Thus, sediments seem to have several sources (*cf.* GREENWOOD, 1969; VISHER, 1969; PYÖKÄRI, 1997), the main ones being local coastal formations and non-local rocks and loose deposits in the river catchment basins. These materials are then mixed by waves and littoral drifts. The negative skewness in the sediments of the surf zone means that they have a tail of coarse, poor rounded material, probably of fluvial origin, consisting mainly of minerals of the silica, feldspar, mafic, epidote and accessory groups, which are derived from the phyllites and quartzites of the inland (Figure 2).

On the other hand, on beaches where no rivers enter the sea or flow near to it (Table 1, Figure 3), sediments on the pocket beaches (Table 1: Beaches F, K, M, P, and R) consist of fine to coarse sand, except the material in the surf zone, which comprises mostly granules or very coarse sand, while on the straight beaches (Beaches A, N, and V) sediments consist of medium sand. The roundness of grains is rather good (sub-rounded to sub-angular, Figure 5), the sediments are well to moderately-well sorted, symmetrical, but mostly negatively skewed in surf-zone sediments, and mesokurtic to slightly leptokurtic (Table 2), consisting mainly of minerals from various mineral groups (Figure 4). This evidence indicates local sources on the adjacent coast (coastal cliffs and rocks) (*cf.* GREENWOOD, 1969; PYÖKÄRI and LEHTOVAARA,

Table 2. *Mean grain size (M_z), degree of sorting (σ_I), skewness (Sk_I), and kurtosis (K_G) of shore sediments in the shore zones on 22 Cretean beaches studied. Beaches A–V are as in Figure 2.*

Location	M_Z (θ)	σ_I	Sk_I	K_G	n
A. Falasarna Beach					
Beach zone	+0.76	0.69	+0.24	1.02	15
Swash zone	+1.31	0.46	−0.22	1.27	15
Surf zone	+1.34	0.56	−0.21	0.89	15
All zones	+1.14	0.57	−0.06	1.06	45
B. Kastelli Beach					
Beach zone	+1.74	0.46	−0.18	1.30	15
Swash zone	+0.53	1.15	−0.20	1.05	15
Surf zone	+2.05	0.45	−0.13	1.39	15
All zones	+1.44	0.69	−0.17	1.24	45
C. Kolimvari Beach					
Beach zone	+0.55	1.08	+0.07	0.90	15
Swash zone	−1.99	0.62	−0.07	0.93	15
Surf zone	+2.56	0.40	−0.31	1.19	15
All zones	+0.37	0.70	−0.10	1.01	45
D. Platanias Beach					
Beach zone	+0.31	0.48	+0.07	1.08	18
Swash zone	+0.53	0.61	−0.00	1.05	18
Surf zone	+0.76	0.66	−0.20	1.45	18
All zones	+0.53	0.58	−0.05	1.19	54
E. Aghia Marina Beach					
Beach zone	+1.82	0.36	+0.01	0.96	18
Swash zone	+1.65	0.32	+0.03	1.01	18
Surf zone	+1.77	0.54	−0.12	1.19	18
All zones	+1.75	0.41	−0.03	1.07	54
F. Kalamaki Beach					
Beach zone	+1.88	0.44	−0.00	0.98	15
Swash zone	+1.98	0.48	−0.08	1.10	15
Surf zone	+2.42	0.46	−0.31	1.03	15
All zones	+2.09	0.46	−0.13	1.04	45
G. Stavros Beach					
Beach zone	+0.47	0.57	+0.12	1.05	15
Swash zone	+0.42	0.45	−0.03	1.14	15
Surf zone	+0.34	0.60	−0.08	1.16	15
All zones	+0.41	0.54	+0.00	1.12	45
H. Kalives Beach					
Beach zone	+0.89	0.71	+0.05	1.12	15
Swash zone	+1.07	0.59	−0.04	1.06	15
Surf zone	+0.97	0.62	−0.16	1.00	15
All zones	+0.98	0.64	−0.05	1.06	45
I. Georgioupolis Beach					
Beach zone	+1.91	0.53	−0.08	1.04	15
Swash zone	+2.02	0.42	+0.02	1.01	15
Surf zone	+2.18	0.53	−0.16	1.54	15
All zones	+2.04	0.49	−0.07	1.20	45
J. Rethymnon Beach					
Beach zone	+1.78	0.37	−0.02	1.33	15
Swash zone	+1.19	0.72	−0.22	1.18	15
Surf zone	+1.02	0.85	−0.06	1.84	15
All zones	+1.33	0.65	−0.10	1.45	45
K. Amnissos Beach					
Beach zone	+1.88	0.31	+0.14	0.96	15
Swash zone	+1.74	0.27	+0.00	0.90	15
Surf zone	+1.73	0.37	−0.01	0.77	15
All zones	+1.78	0.32	+0.04	0.88	45
L. Gouves Beach					
Beach zone	+1.63	0.50	−0.10	1.05	21
Swash zone	+1.56	0.57	−0.08	1.04	21
Surf zone	+0.58	1.30	−0.27	1.44	21
All zones	+1.26	0.79	−0.15	1.17	63

Table 2. *Continued.*

Location	M_Z (θ)	σ_I	Sk_I	K_G	n
M. Hersonissos Beach					
Beach zone	+0.77	0.52	+0.07	1.16	15
Swash zone	−0.15	0.41	+0.05	1.30	15
Surf zone	−1.63	0.78	−0.12	1.11	15
All zones	−0.34	0.57	−0.00	1.19	45
N. Malia Beach					
Beach zone	+1.66	0.33	+0.08	1.07	15
Swash zone	+1.64	0.33	+0.04	1.08	15
Surf zone	+1.59	0.36	−0.02	1.16	15
All zones	+1.63	0.34	+0.03	1.10	45
O. Almiros Beach					
Beach zone	+2.50	0.42	−0.21	1.10	15
Swash zone	+2.42	0.35	−0.09	0.93	15
Surf zone	+2.86	0.33	+0.06	2.78	15
All zones	+2.59	0.37	−0.08	1.60	45
P. Istro Beach					
Beach zone	−0.04	0.56	+0.01	1.48	15
Swash zone	+0.30	0.47	−0.06	1.21	15
Surf zone	−1.63	1.17	−0.10	0.85	15
All zones	−0.46	0.73	−0.05	1.18	45
Q. Sitia Beach					
Beach zone	+0.95	0.56	+0.04	1.17	15
Swash zone	−0.27	0.67	−0.05	1.08	15
Surf zone	−3.42	0.67	+0.02	0.81	15
All zones	−0.91	0.63	+0.00	1.02	45
R. Vai Beach					
Beach zone	−0.00	0.77	−0.08	1.32	15
Swash zone	−0.26	0.56	−0.08	1.28	15
Surf zone	−1.55	0.78	+0.02	1.03	15
All zones	−0.60	0.70	−0.04	1.21	45
S. Ierapetra Beach					
Beach zone	+1.75	0.63	−0.04	1.16	15
Swash zone	+2.13	0.41	+0.14	1.05	15
Surf zone	+0.88	1.26	+0.12	0.92	15
All zones	+1.59	0.77	+0.07	1.04	45
T. Aghia Roumeli Beach					
Beach zone	+0.26	0.71	+0.06	1.51	15
Swash zone	−0.46	1.09	−0.15	0.93	15
Surf zone	−2.50	1.25	+0.21	1.10	15
All zones	−0.90	1.01	+0.04	1.18	45
U. Paleochora Beach					
Beach zone	+1.06	0.93	+0.10	0.81	15
Swash zone	+1.39	0.90	−0.15	1.08	15
Surf zone	+1.90	0.78	−0.17	1.52	15
All zones	+1.45	0.87	−0.07	1.14	45
V. Elafonisi Beach					
Beach zone	+1.68	0.69	−0.18	1.34	30
Swash zone	+2.06	0.38	+0.01	1.30	30
Surf zone	+1.66	0.66	−0.06	1.16	30
All zones	+1.81	0.57	−0.07	1.26	90

n = number of samples

1993; PYÖKÄRI, 1997). The fairly good roundness of the coarse tail of the sediments is also further evidence of coastal sources, because little material (abrasion sediments) reaches these beaches, where particles are carried to and fro by waves and wind-induced currents. As a result the sediment grains are better rounded (*cf.* PYÖKÄRI, 1997). The bay setting of most of the beaches and the highly irregular sea-bottom of

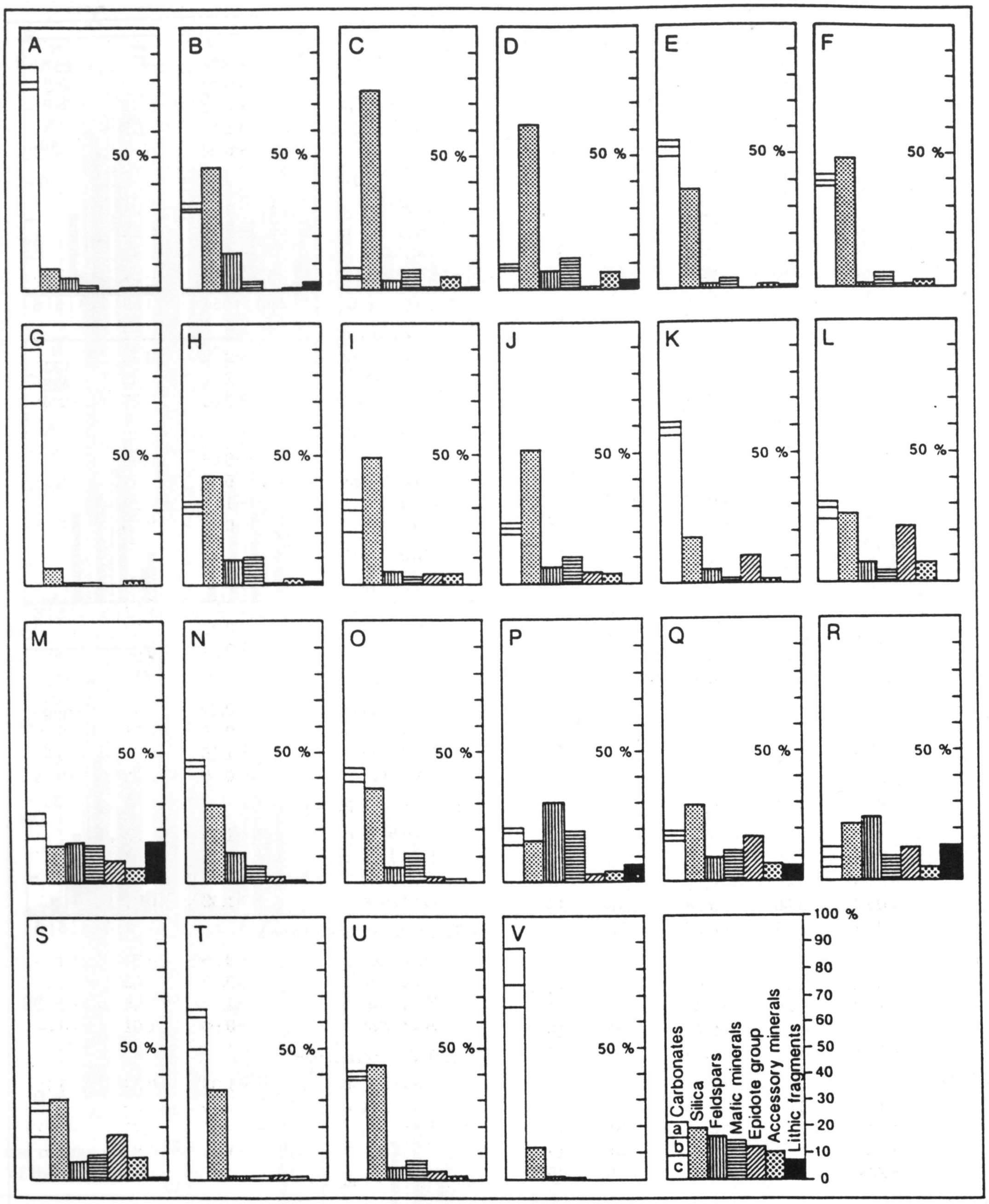

Figure 4. Histograms of mineral and lithic-fragment compositions of representative beach sediment samples at Beaches A–V (as in Figure 2). Part a in the carbonate column is the proportion of aragonite and high-Mg calcite, part b the proportion of dolomite and magnesite, and part c the proportion of low-Mg calcite.

the bay further preclude any significant longshore supply of sediment. In other words, the bulk of the beach sand is local cliff- and bluff-derived with the exceptions of Beaches A and V on the western coast, where large waves carry carbonate sand along the shore from a greater distance and where tectonic uplift is rapid (POSTMA and NEMEC, 1990), causing a wide beach.

Rather poor roundness of sediment grains on the beaches of Crete, in general, and above all of non-carbonate grains, suggests that the transport distances for material in littoral drifts are nowhere very great. The roundness of the grains and the length of the beach also depend somewhat on each other, because the frequency distribution of the roundness of all sediment grains is the same on some beaches which have nearly the same length (*e.g.,* Beaches F, O and R or C and D) (Table 1, Figures 3 and 5). This same dependence can also be

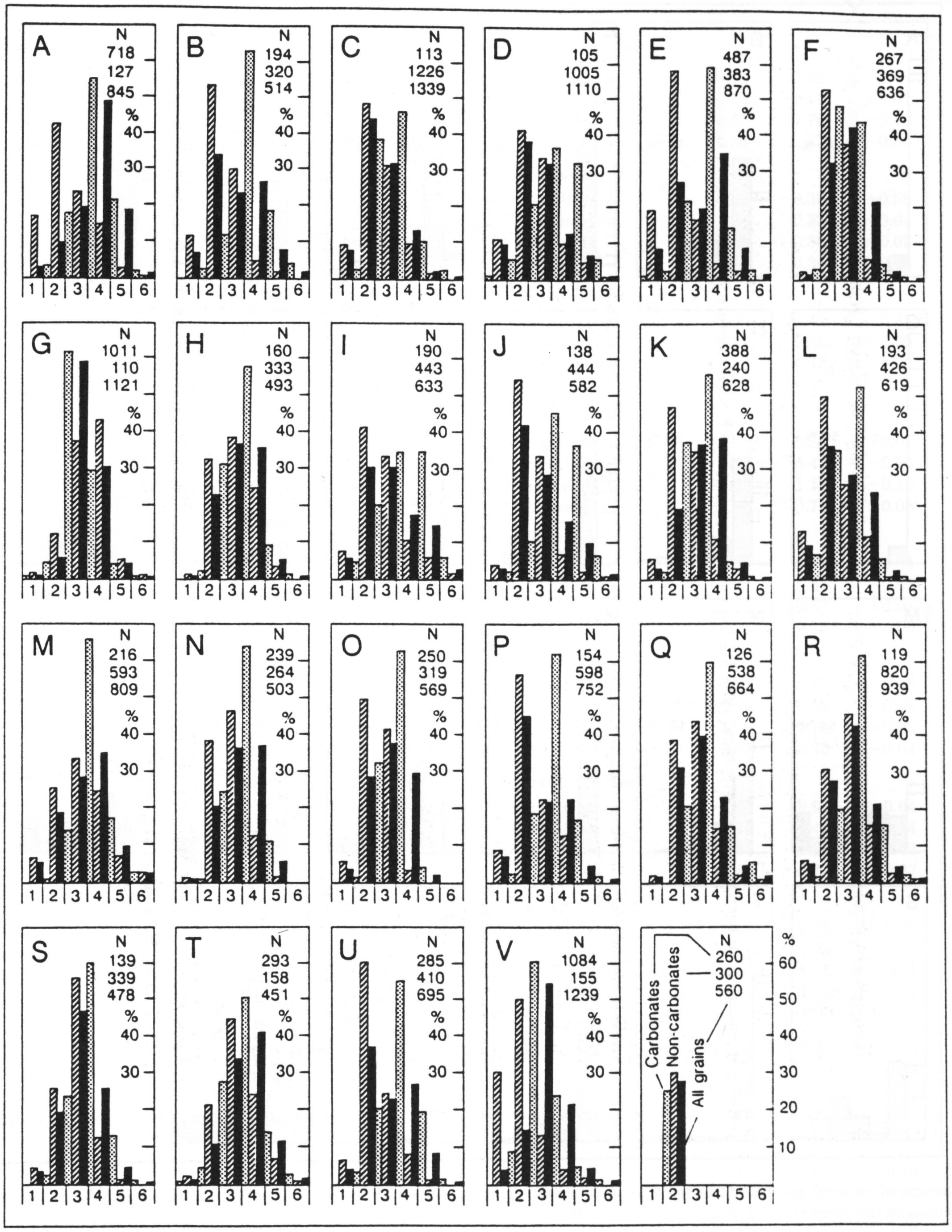

Figure 5. Roundness of sediment grains of representative beach sediment samples on Beaches A–V (as in Figure 2). Classes (based upon Powers, 1953): (1) very angular, (2) angular, (3) sub-angular, (4) sub-rounded, (5) rounded, (6) well-rounded. (N) number of grains studied.

seen in the roundness of the carbonate grains (*e.g.,* Beaches H, K and O or D and I), while the roundness of the non-carbonate clasts seems to depend more on the minerals of which the different beach sands consist (*e.g.,* Beaches B and C or R and S) (Figures 4 and 5). The roundness does not seem to be related to grain size.

Cliffs, bluffs and slightly hardened Pleistocene deposits on the coasts provide a ready sediment supply for beach sand. The mineral suites of these formations (limestones, marly limestones, dolomitic limestones, flysch, sandstones, sandy marls, marls and phyllites-quartzites) (CREUTZBURG *et al.,* 1977) are rich in such minerals as low-Mg calcite, dolomite,

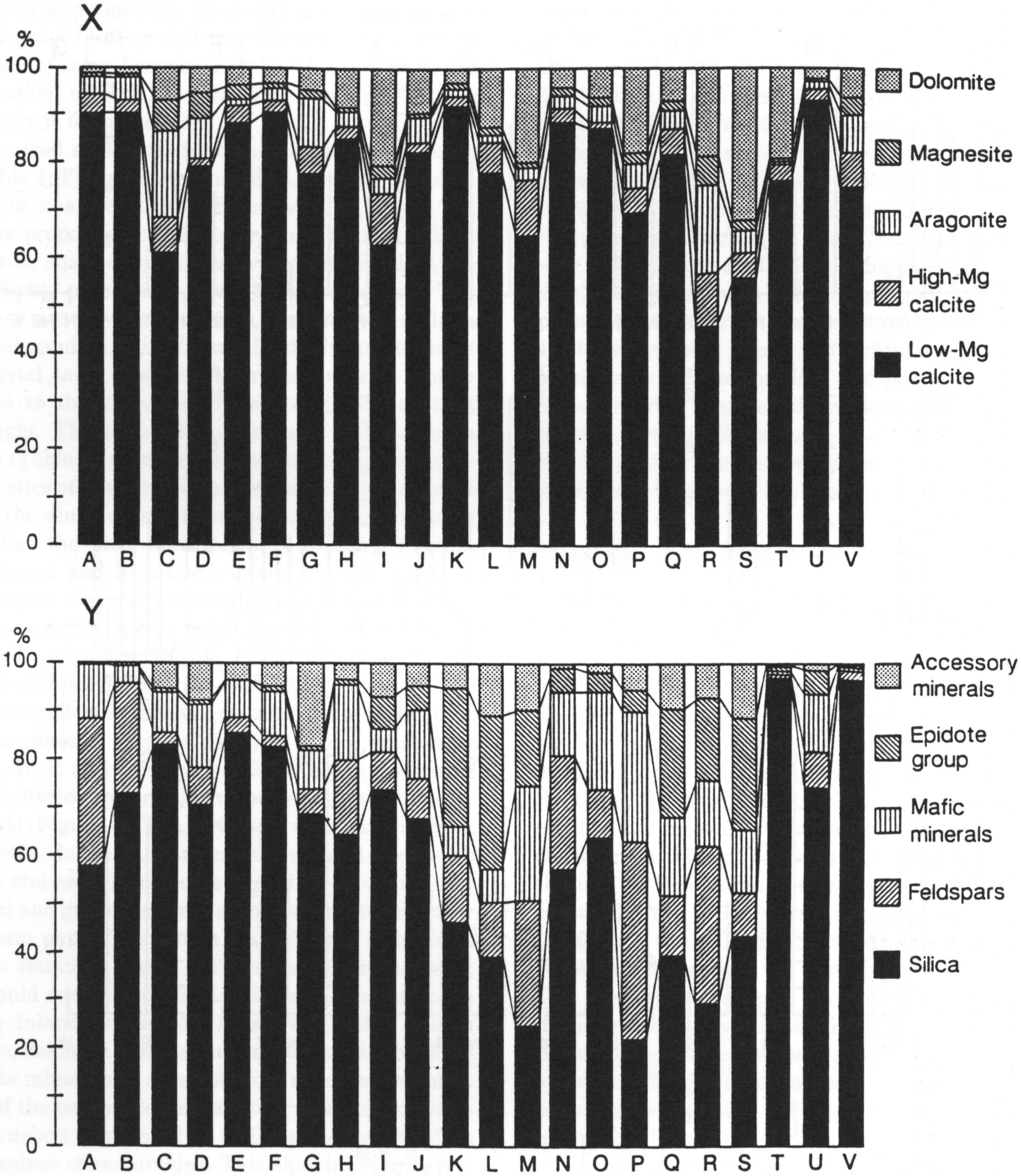

Figure 6. Stacked column chart of minerals. (X) Carbonate minerals (100%). (Y) Non-carbonate minerals (100%). Samples studied were representative for each section of the beaches. Beaches A–V are the same as in Figure 2.

quartz, chert, feldspars, pyroxenes, amphibolites and epidotes, which also dominate the content of beach sand (Figure 4). This is clearly seen, for example, in the increasing dolomite (11.5%) and chert (32.5%) proportions of the sediments of Beach T (Figure 3), where the shore rocks consist of limestones and dolomitic limestones with plenty of chert layers (CHRISTODOULOU and TATARIS, 1969; BONNEAU, 1984). It can also be seen in the sediments of Beaches A, G and V, which are located in nearly pure limestone areas (KARAGEORGIOU and BIZON, 1970; KARAGEORGIOU and TSAÏLA-MONOPOLI, 1971; CREUTZBURG *et al.*, 1977) so that the carbonate proportions in the sands are high (85–90%) and the frequency distributions of the mineral contents are same (Figure 4). Another example is the sediments on Beaches N and O, where the frequency distributions of the mineral contents are the same (Figure 4) as are also the relative proportions of carbonate and non-carbonate minerals (Figure 6). This is due to the fact that the sediments on both the beaches are derived from the same limestone and marl formations (Figure 2) (CREUTZBURG *et al.*, 1977; KNITHAKIS *et al.*, 1987; VIDAKIS *et al.*, 1993). On pocket beaches and straight beaches where rivers neither discharge on to or near the beach

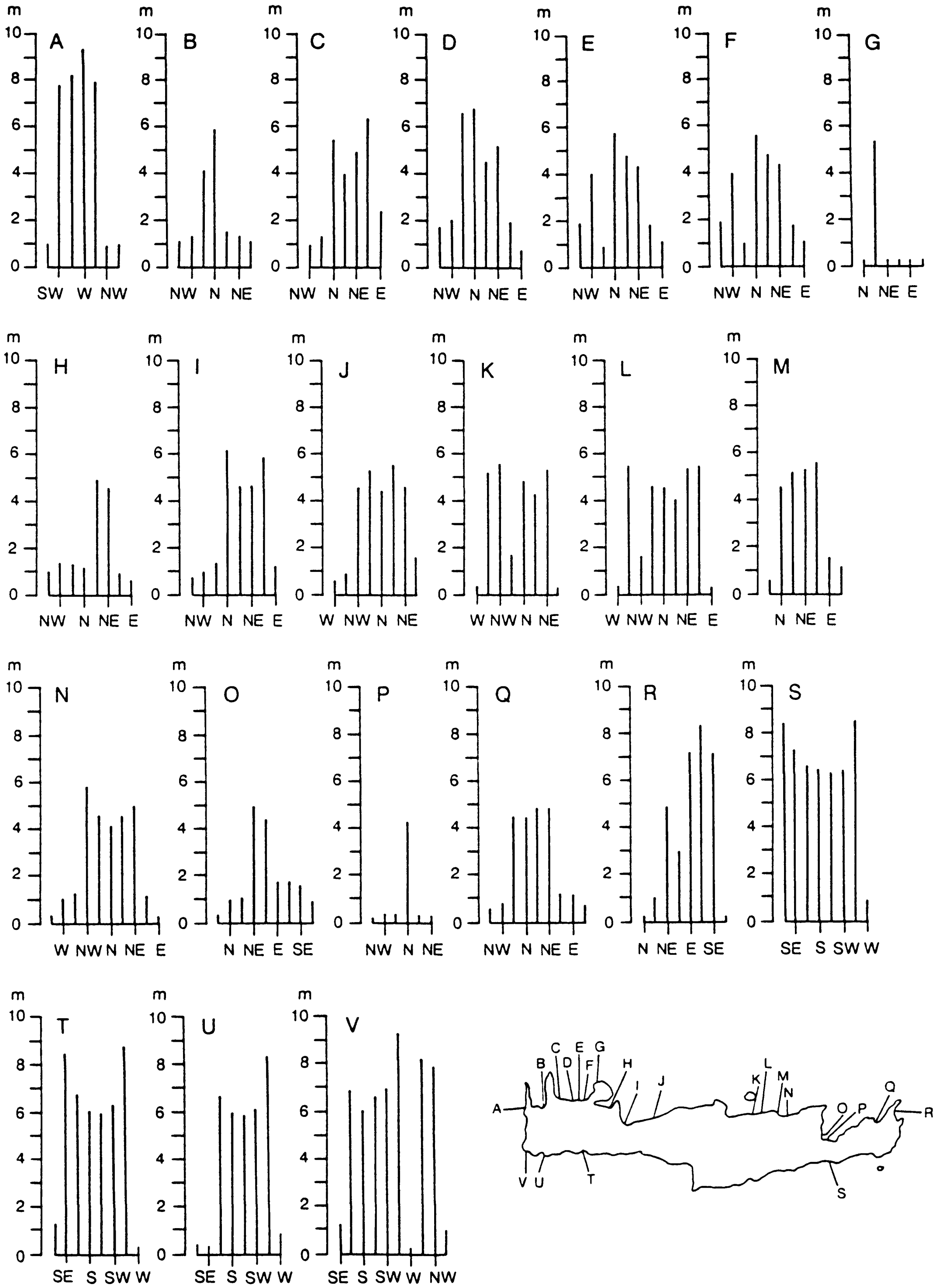

Figure 7. Estimated theoretical wave heights (in metres) for minimum wind durations (velocity 21 m/s) according to fetch conditions (Bretschneider, 1959) on the beaches studied on Crete. Beaches A–V are as in Figure 2.

(Beaches A, F, K, M, N, P, R and V), the sources of sediments are coastal rocks and deposits, most of them being in close proximity to coastal bluff or cliff (*e.g.,* Figure 3: Beaches M and P). On some of these beaches (*e.g.,* Beaches A and V) the finest dry reworked material is carried by winds behind the backshore, where it forms dunes.

Where rivers feed sediments from the drainage area on to the beach (Table 1; Figure 3: Beaches B–E, H–J, L, Q and S) or to the end or near the beach (Beaches G, O, T and U), there is a large proportion of quartz grains (Figure 4) which are angular with sharp edges (Figure 5: class angular), indicating a differing provenance, river-borne sediments. The sources of these are phyllite-quartzite, sandstone, conglomerate, marl and sand deposits from inland (CREUTZBURG *et al.,* 1977). Fluvial sand in short mountain rivers is rapidly transported on to the shore during winter floods, so that wearing is slight. The textural properties of sediments on these beaches (Table 2) seem to depend more on the grain-size characteristics of material from the river catchment area than those of the abrasion sediments. Shore forces have affected somewhat the size characteristics of sand fraction (negatively skewed and leptokurtic material with a poorly sorted tail of coarse material), but only the amount of gravel proportion in sediments, not so much its size characteristics (*cf.* VISHER, 1969; PYÖKÄRI, 1987).

The mineral composition of the carbonate group on the beaches of Crete indicates that the sources of the carbonates is nearly homogeneous (Figure 4) with a few exceptions (Beaches C, I, M, R and S). Small differences in the source materials are reflected in the relative percentages of the carbonate minerals (Figure 6). The carbonate sand derives from limestone, marble, dolomite, marl, calcsilicate and calcareous phyllite rocks and weakly cemented marine, fluviatile and lacustrine sand and gravel deposits along the coasts and river banks. The main part of carbonate clasts seems to be from sub-angular to rounded, which indicates abrasion material, while some would seem to be angular, indicating river-borne material from inland (Figure 5). Relatively stable phases (low-Mg calcite, dolomite and magnesite) constitute the dominant carbonate minerals in abrasion- and river-borne sands. A small part of the carbonates are angular bioclasts, consisting of skeletal debris dominated by mollusc and foraminifera particles and spines of sea urchins. This skeletal debris, produced on the adjacent narrow shelf, carried by waves and currents on to the beach and trapped from moving material into the interstices of coarse sediments, is a major source of aragonite and high-Mg calcite (*cf.* PYÖKÄRI and LEHTOVAARA, 1990, 1993; PYÖKÄRI, 1997). These less stable carbonates (aragonite and high-Mg calcite) are most common in the carbonate sand on Beaches G and V (Figure 4) and in the relative proportions of the carbonates on Beaches C, R, I and M (Figure 6).

The phyllite-quartzites, ophiolites (serpentinised peridotites, gabbros, amphibolites, gneisses), mafic volcanites (diabase, pillow lava, spilite, basalt, andesite) and ultramafic rocks (mainly serpentinised peridotites) (CREUTZBURG *et al.,* 1977) are common on Crete (Figure 2). A large epidote proportion (13–18%) on the eastern Crete in the sediments of Beaches Q, R and S (Figure 4) originates mainly from the rocks of the phyllite-quartzite series, consisting of siliciclastics and impure carbonates, and of pyroclastic, volcanic and minor intrusive igneous rocks situated on the coast or near the coast (Figure 2) (CREUTZBURG *et al.,* 1977; BONNEAU, 1984; HALL *et al.,* 1984; KNITHAKIS *et al.,* 1987; VIDAKIS *et al.,* 1993). This proportion displayed nearly the same relative proportions of the non-carbonate mineral groups in the beach sediments (Figure 6). These rocks have deformed and metamorphosed, the grade of metamorphism varying from very low grade greenschist in east Crete to blueschist facies in west Crete (HALL *et al.,* 1984). The platy limestones (Plattenkalk) have also been metamorphosed and their metamorphism increases from western to eastern Crete (BONNEAU, 1984; KNITHAKIS *et al.,* 1987). Mafic minerals (pyroxenes, amphiboles and tourmaline) and partly also accessory minerals (garnets, titanite, zircon, magnetite and apatite) in the beach sediments (Beaches C, D, J, M–S and U) are also derived from these same formations on the coast or in the river-catchment areas near the coast (Figures 2, 4 and 6).

Transport of Sediments and Direction of Littoral Drift

The greatest fetches on Crete (and fetches in general) are situated on the W, E and S coasts, being much longer (830–1100 km) than those on the N coast (130–330 km) (Figures 1 and 2). On these coasts (Beaches A, R and S–V) there are no sheltering promontories, so the estimated wave heights are also much higher, and waves reach higher up the beach than on the N coast (Figure 7: Beaches B–Q), where large headlands are frequent (Figure 2). Sediment transport on the S coast seems to be eastwards in all the shore zones except in the swash and beach zones on Beach S, where it is westwards (Figure 8). Predominant waves (mostly swells) come to this coast from the WSW, where the fetch is greatest. However, the fetches to the ESE–SSE are nearly as great as from the WSW, which explains the movement to the west on Beach S. The northward transport on Beach A on the W coast and movement towards the north and south on Beach V on the SW corner of Crete are also caused by the predominant western wind. The directions of the greatest fetch (E–SE) and the second greatest fetch (NE) also explain the opposite movement directions in the surf zone (towards N) and in the swash and beach zones (towards S) on Beach R (Figure 7).

The direction of littoral drift on the beaches on the N coast is complex, because some beaches are situated on the leeside of the promontories in relation to the prevailing NW wind (Figures 2 and 3: Beaches B, C, H, I, M, O and Q), some are pocket beaches at the head of small coves (Beaches F, G and P), and some have two maximum fetches (Table 1; Figures 7 and 8: Beaches E, F, K and L). The direction of the greatest fetch also varies on separate beaches (Figures 2, 7 and 8). The movement eastward in the shore zones is caused partly by the prevailing wind (*e.g.,* Beaches B, D, H and Q), and partly by the prevailing and predominant winds together (*e.g.,* Beaches E, I, K, L and N). The westward movement is caused mainly by the predominant waves (mostly swells), which reach these beaches from the NE (Figure 7: *e.g.,* Beaches C, J, L, M and Q), and partly by a local reversal in the direction of littoral drift in the lee of the headland caused by the refraction and diffraction of the waves around the headland (Figures 2–3: Beaches B, C, H, I, M, O and Q) (*cf.* YASSO, 1965; JACOBSEN and SCHWARTZ, 1981; TAGGART and SCHWARTZ, 1988; PYÖKÄRI and LEHTOVAARA, 1991). The influences of wave refraction and diffraction to the directions of littoral drift are most evident on the pocket beaches (Beaches F, G and P), where the movement is towards the bayhead, or refraction and diffraction cause local reversals in littoral-drift direction (Beach F) (Figures 3 and 8).

Where the inshore of the beach is deep, deposition occurs only on the foreshore on berms (Beaches D, P and T) (Table 1; Figure 8), but where the inshore is more gently sloping or shallow, the beach can be depositional or erosional. Deposition is on to the berms and beach ridges on the foreshore and on to the bars on the inshore due to the transport offshore-onshore (Table 1). On the shallow Beach V (Figures 3 and 7) strong deposition occurs on to the spits and crescent bars. When the means of the grain-size parameters of the samples from each beach profile from each shore zone on beaches A–V were tested in the transport direction and normal to the shore using the Student's t-test, the grain-size parameters differed significantly in most cases. Thus, the directions of littoral drift and onshore-offshore transport (Figure 8) would seem reliable.

Judging from beach-sediment composition and some geomorphic indicators (*e.g.,* sedimentation against jetties, widening of backshore, bluff morphology, stream mouth diversions) (TAGGART and SCHWARTZ, 1988) net littoral drift on the S coast of Crete seems to be eastwards (Figure 8), caused by the predominant wind (Figure 7). On the N coast the direction of net littoral drift is on some beaches eastwards and on other beaches towards the west, induced mainly by the predominant wind. The direction of net littoral drift to the north on Beach A on the W coast and southwards on Beach R is also probably caused by the predominant wind.

Using Spearman's coefficient of rank correlation (non-parametric test) (KENDALL, 1962), the direction of littoral drift was tested against the directions of most common wind direction in summer and winter (prevailing wind), the most effective wind direction (predominant wind or length of the fetch) and the onshore wind directions arranged according to the length of the fetch, the principal factors affecting the directions of sediment transport (Table 3). It seems that the direction of net littoral drift depends largely on the direction of the greatest wind fetch (or predominant wind and waves). The correlation (0.79) in Table 3 is significant. A fairly significant correlation (all zones 0.57) is also between the directions of onshore winds and seasonal littoral drift, but only in the transport of swash-zone (0.57) and surf-zone (0.58) sediments. The direction of the greatest fetch also seems to determine to a large extent the direction of seasonal littoral drift in the surf zone; the correlation is fairly significant (0.61). There are only indicative correlations (0.44, 0.46) between the directions of the prevailing wind and seasonal littoral drift in the beach zone and no correlations in the other zones.

Thus, the direction of the greatest fetch (predominant waves and wind) on the coasts of Crete seems to be the most significant factor determining the direction of littoral drift and partly the direction of seasonal sediment movement in the surf zone. The significant factor which determines the direction of the seasonal littoral drift, appearing best in the sediment movement in the swash and surf zones, is the approaching directions of onshore waves and winds arranged according to the length of fetch. On the other hand, the direction of the prevailing wind does not seem to determine the direction of sediment movement on the coasts of Crete. Taken all together, the results of this study emphasize the significance of the directions of wind fetches in determining the direction of sediment transport on the coasts of Crete.

CONCLUSIONS

(1) Texture and composition of beach sediments and roundness of grains vary with some exceptions, displaying patterns that are consistent with coastal formations and those in the catchment basins of the rivers, and the processing acting on the coasts. The geological homogeneity of the areas is also reflected in the homogeneity of mineral content and texture of beach sediments and in the roundness of sediment grains (Table 2; Figures 4–6). However, where there are exceptions from the general homogeneity, above all in the coastal rocks, as on eastern Crete, these are also reflected in sediments.

(2) Sediments consist mainly of medium and coarse sand; they are, in general, moderately-well or well sorted, symmetrical or negatively skewed and meso- or leptokurtic (Table 2). The composition of beach sediments consists of either a large proportion of carbonates or of silica minerals or both of them (Figure 4). Minerals of the feldspar, mafic and epidote groups are common on some beaches, particularly on eastern Crete. Low-Mg calcite and quartz are the most frequent minerals, making up, in general, altogether 50–90% of the mineral composition. Dolomite, plagioclase, epidotes, pyroxenes, amphiboles, tourmaline, titanite, zircon, and magnetite are also common, other minerals being rare. The roundness of carbonate particles in beach sediments is better than that of non-carbonates, sub-angular, angular and sub-rounded grains being generally most frequent (Figure 5).

(3) The mineral composition of beach sediments (predominantly low-Mg calcite and quartz) on beaches where no rivers enter the sea or flow near to it and the rather high degree of roundness of sediment grains (mainly from sub-angular to rounded) suggest that the main sources of the sand and gravel are abraded adjacent coastal formations (cliffs, bluffs, rocks or sand and gravel deposits). A small proportion of carbonates (high-Mg calcite and aragonite) are, however, derived from the nearby shelf. Where rivers discharge on to the beach or near to it, the mineral content and the roundness of grains indicate that a great part of beach sediments originate from formations situated in the catchment basins of the rivers. This material and material abraded from coastal formations are mixed by waves and littoral drifts causing somewhat poorer sorting of beach material and roundness of grains, and also making the grain-size distribution of surf-zone sediments negative, which means that they have a tail of coarse, angular material, probably of fluvial origin.

(4) The direction of net littoral drift on the beaches is de-

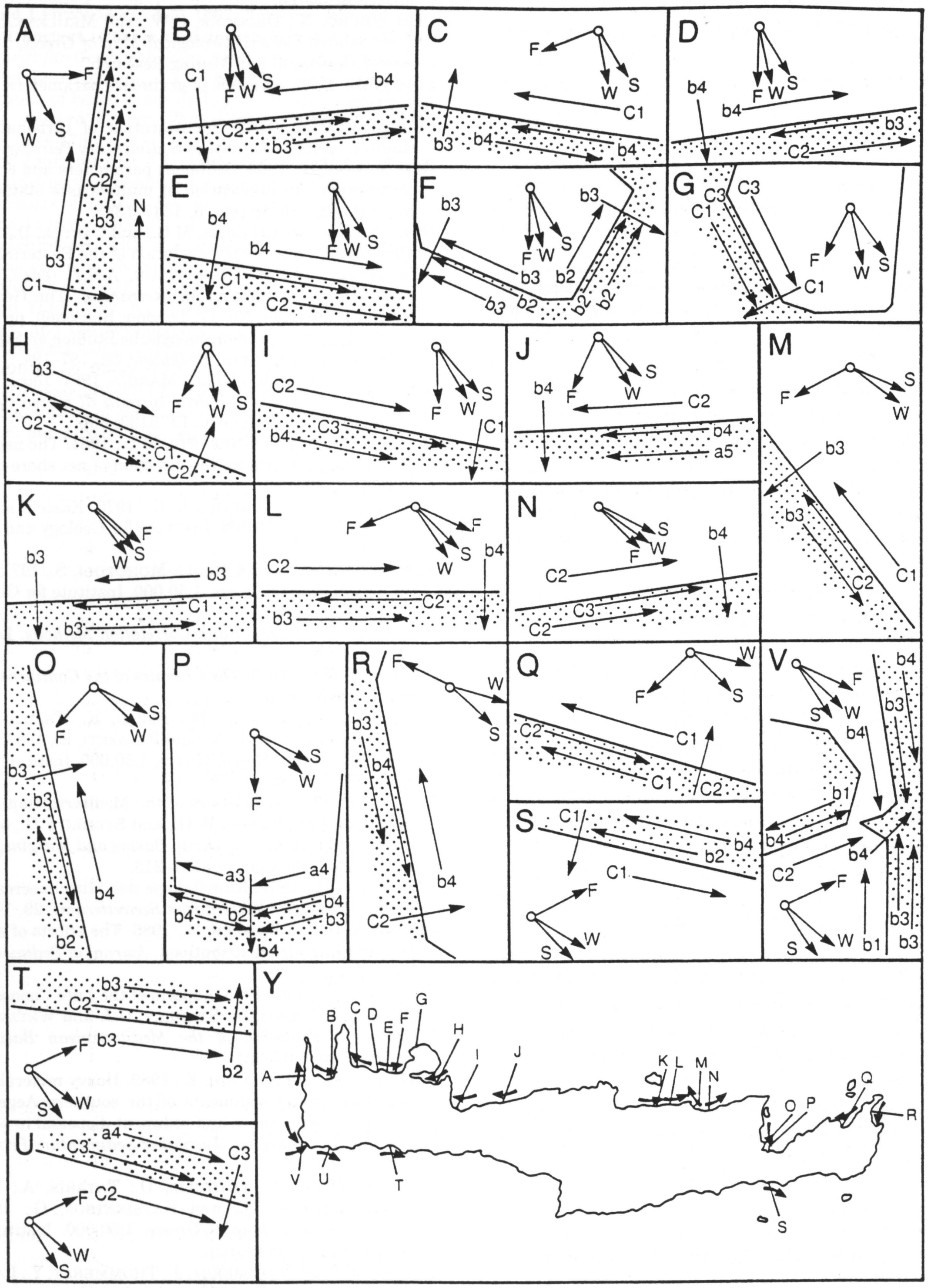

Figure 8. Direction of transport on the beaches studied. Key: (Figures A–V) The directions of littoral drift (beach drift and longshore drift) in the three shore zones and transport of sediments normal to the shore along the studied lines on the beaches are indicated by arrows (a = exclusively, b = mostly, c = mainly). Sediment transport in the direction of arrow is very strong (5), strong (4), moderate (3), weak (2) or very weak (1). (S) Direction of prevailing wind in summer, (W) direction of prevailing wind in winter, (F) direction of the estimated oncoming heighest waves (direction of the largest fetch). (Figure Y) The direction of net shore drift. Beaches A–V are as in Figure 2.

Table 3. *Dependence of direction of littoral drift on the directions of prevailing wind, predominant wind, and onshore winds.*

Littoral Drift	Prevailing Wind, Summer r_s	Prevailing Wind, Winter r_s	Predominant Wind r_s	Onshore Winds † r_s
Seasonal drift				
Beach zone	+0.44°	+0.46°	+0.26	+0.31
Swash zone	+0.17	−0.27	+0.23	+0.57*
Surf zone	+0.08	−0.21	+0.61*	+0.58*
All zones	+0.19	−0.01	+0.44°	+0.57*
Net littoral drift	+0.15	+0.22	+0.79**	+0.50°

r_s = Spearman's coefficient of rank correlation, arranged according to the effects of the waves on the shore in relation to the directions of prevailing or predominant winds.
†r_s = Arranged according to the length of fetch.
° = correlation indicative (risk 0.1).
* = correlation fairly significant (risk 0.05).
** = correlation significant (risk 0.01).

termined mainly by the predominant wind and waves (Table 3), whereas the most significant factor determining the direction of seasonal littoral drift is the directions of the fetches arranged according to the length of fetch (onshore winds and waves). The direction of the predominant wind also largely determines the direction of seasonal sediment movement in the surf zone together with the onshore winds, while in the swash zone it is determined solely by the onshore winds. In the beach zone the direction of seasonal drift is determined rather weakly by the prevailing wind and waves, but the direction of prevailing wind does not, in general, seem to determine the direction of sediment movement on the beaches of Crete. Where the inshore is deep, deposition occurs only on the berms, but where the inshore is gently sloping or shallow, deposition occurs on to the berms or beach ridges on the foreshore and on to the bars inshore.

ACKNOWLEDGMENTS

I wish to thank Mrs. Leena Kiiskilä, who drafted the figures in the final form, Mr. Christopher Grapes, who corrected the English text, my late wife Mrs. Maire Pyökäri and my son Mr. Heikki Pyökäri, who helped in collecting the samples. This study was supported financially by the Foundation of the University of Turku and by a scholarship from the Greek state (collaborating with the Finnish Centre for International Mobility and Exchange Programs). Without this financial help it would have been very difficult to make this study.

LITERATURE CITED

ALLMAN, M. and LAWRENCE, D., 1972. *Geological Laboratory Technics.* London: Blandford Press, 335p.

BONNEAU, M., 1984. Correlation of the Hellenides nappes in the south-east Aegean and their tectonic reconstruction. *In:* DIXON, J.E. and ROBERTSON, A.H.F., (eds.), *The Geological Evolution of the Eastern Mediterranean.* The Geological Society Special Publication No. 17. London: Blackwell, pp. 517–527.

BRETSCHNEIDER, C.L., 1959. Revisions in wave forecasting, deep and shallow water. *In: Proceedings of the 3rd Conference on Coastal Engineering,* pp. 30–67.

CHRISTODOULOU, G.E. and TATARIS, A.A., 1969. Alikianou sheet. *Geological Map of Greece,* 1:50,000. Institute for Geology and Subsurface Research.

CREUTZBURG, N.; DROOGER, C.W., and MEULENKAMP, J.E., 1977. Crete Island. *General Geological Map of Greece,* 1:200,000. Institute of Geological and Mining Research.

FOLK, R.L., 1966. A review of grain-size parameters. *Sedimentology,* 6, 73–93.

FRIEDMAN, G.M., 1959. Identification of carbonate minerals by staining method. *Journal of Sedimentary Petrology,* 29, 87–97.

GREENWOOD, B., 1969. Sediment parameters and environment discrimination: An application of multivariate statistics. *Canadian Journal of Earth Science,* 6, 1347–1358.

HALL, R.; AUDLEY-CHARLES, M.G., and CARTER, D.J., 1984. The significance of Crete for the evolution of the Eastern Mediterranean. *In:* DIXON, J.E. and ROBERTSON, A.H.F. (eds.), *The Geological Evolution of the Eastern Mediterranean.* The Geological Society Special Publication No. 17. London: Blackwell, pp. 499–516.

HEMPEL, L., 1984. Geomorphologische Studien an Schuttfächern (alluvial fans) in Ostkreta. *Erdkunde,* 38, 187–194.

ISTITUTO IDROGRAFICO DELLA MARINA, 1981. *Tavole di marea (Mediterraneo—Mar Rosso) e delle correnti di marea (Venezia—Stretto di Messina), 1982.* Genova: I.I. 3133, 89p.

JACOBSEN, E.E. and SCHWARTZ, M.L., 1981. The use of geomorphic indicators to determine the direction of net shore-drift. *Shore and Beach,* 49, 38–43.

KARAGEORGIOU, E. and BIZON, G., 1970. Kastelli sheet. *Geological Map of Greece,* 1:50,000. Institute for Geology and Subsurface Research.

KARAGEORGIOU, E. and TSAÏLA-MONOPOLI, S., 1971. Khania sheet. *Geological Map of Greece,* 1:50,000. Institute for Geology and Subsurface Research.

KENDALL, M.G., 1962. *Rank Correlation Methods.* London: Edward Arnold, 199p.

KENDREW, W.G., 1953. *The Climates of the Continents.* Oxford: Clarendon Press, 607p.

KNITHAKIS, E.; VIDAKIS, M.; BEZES, K.; TSAÏLA-MONOPOLI, S.; SKOURTSI-KORONEOU, V., and PAPAZETI, E., 1987. Ayios Nikolaos Sheet. *Geological Map of Greece,* 1:50,000. Institute of Geology and Mineral Exploration.

LORT, J.M., 1977. Geophysics of the Mediterranean Sea Basins. *In:* NAIRN, A.E.M.; KANES, W.H., and STEHLI, F.G., (eds.), *The Eastern Mediterranean, The Ocean Basins and Margins,* 4 A. New York and London: Plenum, pp. 151–213.

MARKGRAF, H., 1961. Klimatologie des Mittelmeeres, Teil 1: Windkarten. *Deutscher Wetterdienst Seewetteramt,* 29, 1–99.

MCLAREN, P. and BOWLES, D., 1985. The effects of sediment transport on grain-size distributions. *Journal of Sedimentary Petrology,* 55, 457–470.

MEULENKAMP, J.E., 1985. Aspects of the Late Cenozoic Evolution of the Aegean Region. *In:* STANLEY, D.J. and WETZEL, F.-C., (eds.), *Geological Evolution of the Mediterranean Basin.* New York: Springer, pp. 307–321.

MEZZARDI, G. and SACCANI, E., 1989. Heavy mineral distribution in Late Quaternary sediments of the southern Aegean Sea: Implications for provenance and sediment dispersal in sedimentary basins at active margins. *Journal of Sedimentary Petrology,* 59, 412–422.

PAPASTAMATIOU, J.; VETOULIS, D.; TATARIS, A.; BORNOVAS, J.; CHRISTODOULOU, G., and KATSIKATSOS, G., 1959. Ierapetra sheet. *Geological Map of Greece,* 1:50,000. Institute for Geology and Subsurface Research.

PIRAZZOLI, P.A.; THOMMERET, J.; THOMMERET, Y.; LABOREL, J., and MONTAGGIONI, L.F., 1982. Crustal block movements from Holocene shorelines: Crete and Antikythira (Greece). *Tectonophysics,* 86, 27–43.

POSTMA, G. and NEMEC, W., 1990. Regressive and transgressive sequences in a raised Holocene gravelly beach, southwestern Crete. *Sedimentology,* 37, 907–920.

POWERS, M., 1953. A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology,* 23, 117–119.

PYÖKÄRI, M., 1997. The provenance of beach sediments on Rhodes, southeastern Greece, indicated by sediment texture, composition and roundness. *Geomorphology,* 18, 315–332.

PYÖKÄRI, M. and LEHTOVAARA, J.J., 1987. Texture, mineral composition, and transport of shore material on Mamaia Beach, Romania. *Zeitschrift für Geomorphologie, Neue Folge,* 31, 473–487.

PYÖKÄRI, M. and LEHTOVAARA, J.J., 1990. Texture, composition, and sedimentation of beach sands on Lagana Beach on the island of Zakynthos, western Greece. *Zeitschrift für Geomorphologie, Neue Folge,* 34, 459–473.

PYÖKÄRI, M. and LEHTOVAARA, J.J., 1991. The nature, source and directions of transport of beach materials on the southern and southwestern coasts of Cyprus. *Fennia,* 169, 183–202.

PYÖKÄRI, M. and LEHTOVAARA, J.J., 1993. Beach material and its transport in accordance with the predominant and prevailing wave directions on some shores in northern Greece. *Journal of Coastal Research,* 9, 609–627.

PYÖKÄRI, M. and YLI-KYYNY, K., 1995. Volcanic beach sediments, their transport, and the development of shore platforms at the base of the caldera wall on the Santorini islands, southern Greece. *Journal of Sedimentary Research,* A 65, 436–443.

ROBERTSON, A.H.F. and DIXON, J.E., 1984. Introduction: Aspects of the geological evolution of the Eastern Mediterranean. *In:* ROBERTSON, A.H.F. and DIXON, J.E., (eds.), *The Geological Evolution of the Eastern Mediterranean.* Geological Society Special Publication No. 17. London: Blackwell, pp. 1–74.

SACCANI, E., 1987. Double provenance of sand-size sediments in the southern Aegean forearc basin. *Journal of Sedimentary Petrology,* 57, 736–745.

TAGGART, B.E. and SCHWARTZ, M.L., 1988. Net shore-drift direction determination: A systematic approach. *Journal of Shoreline Management,* 3, 285–309.

VANNEY, J.-R. and GENNESEAUX, M., 1985. Mediterranean seafloor features: overview and assesment. *In:* STANLEY, D.J. and WETZEL, F.-C., (eds.), *Geological Evolution of the Mediterranean Basin.* New York: Springer-Verlag, pp. 3–32.

VIDAKIS, M.; MEULENKAMP, J.E.; JONKERS, H.A.; SKOURTSI-KORONEOU, V.; PAPAZETI, E., and VARTI-MATARANGA, M., 1989. Mochos sheet. *The Geological Map of Greece,* 1:50,000. Institute of Geology and Mineral Exploration.

VIDAKIS, M.; FORTUIN, A.R.; PAPAZETI, E., and SKOURTSI-KORONEOU, V., 1993. Ierapetra sheet. *Geological Map of Greece,* 1: 50,000. Institute of Geology and Mineral Exploration.

VISHER, G.S., 1969. Grain size distributions and depositional processes. *Journal of Sedimentary Petrology,* 39, 1074–1106.

YASSO, W.E., 1965. Plan geometry of headland-bay beaches. *Journal of Geology,* 73, 702–714.