FACIES	42	227-244	Pl. 44-47	7 Figs.	--	ERLANGEN 2000

Rocky Shore-Gravelly Beach Transition, and Storm/Post-storm Changes of a Holocene Gravelly Beach (Kos Island, Aegean Sea): Stratigraphic Significance

Diethard **Sanders**, Innsbruck

KEYWORDS: TRANSGRESSIVE RECORD – GRAVELLY BEACH – BEACH CHANGES – KOS-ISLAND (GREECE) – RECENT

CONTENTS

SUMMARY

On Kos island, Greece, along an investigated coastal segment 3 km in length, four adjacent sectors were distinguished, (1) Empros beach, a rocky shore with plunging cliffs and a steeply dipping, submarine talus, (2) Thermi beach, a „coarse-clastic beach" with a subaerial cliff fringed by a bouldery to coarse gravelly beach with poorly developed zonation, (3) Dimitra beach, a gravelly beach with well-developed zonation, and (4) Phokas beach, a gravelly beach characterized by finer mean grain size. The lateral variation in Holocene coastal morphology would lead to different transgressive records: „rapid" sea-level rise that may be suggested by transgression of the rocky shore is contemporaneous with „gradual" rise recorded by transgression of the gravelly beaches.

Dimitra beach is an about 500 m long, cuspate, microtidal, wave-dominated gravelly beach. From land offshore, in its fairweather configuration it shows
(a) a backshore of rounded gravels to small, rounded boulders,
(b) a winter storm berm paved by disc-shaped clasts,
(c) a belt of beach cusps each centered by an oblique-triangular foreshore sand flat, and flanked by gravel ridges of roughly triangular shape in plan view,
(d) a fairweather plunge step,
(e) a „relic storm/swell beachface" (uppermost shoreface during fairweather) of clean, rounded coarse gravels to cobbles,
(f) a storm/swell plunge step, and
(g) a veneer of gravels to boulders that, farther seaward, grades into submarine sand flats.

During storm upbuilding, the foreshore sand flats disappeared, the gravel ridges were eroded and an even, more gently dipping storm beachface developed. Beach restoration in a swell regime proceeded in feedback with the emergent fairweather beach morphology. During ensuing fairweather, the foreshore sand flats were partly winnowed. On Dimitra beach, the layer involved in beachface to uppermost shoreface dynamics was about 1 m thick and 10-15 m wide. In fossil gravelly beach successions, features formed during high-energy events include both berms and master bedding surfaces. Features of the waning stage are fairweather plunge steps and relic storm/swell beachfaces (lower beachface). From cuspate gravel ridges of the upper beachface probably only the basal part is preserved.

1 INTRODUCTION

Papers on gravelly beaches and rocky shores are comparatively rare, although these coasts are fairly common (Bluck 1967; DoBkins & Folk 1970; Maejima 1982; Bourgeois & Leithold 1984; Nemec & Steel 1984; Johnson 1988; Massari & Parea 1988; Hart & Plint 1995; Sanders 1997, 1998). Most studies on gravelly beaches come from fossil gravelly shore zone deposits (see Massari & Parea 1988; Hart & Plint 1995, and references therein). The morphology of gravelly beaches is mainly controlled by the mean grain size of the coarse sediment fraction, by the amount of sand present in the system, by wave climate and nearshore currents, tidal range, and sediment input (Kirk 1980; Forbes & Taylor 1987; Hart & Plint 1995). The influence of all these parameters on both beach morphology and sedimentary structures may explain the differences in the proposed schemes for the vertical development of gravelly beaches (see Bluck 1967; Maejima 1982; Emery & Myers 1996).

Address: Dr. D. Sanders, Institut für Geologie und Paläontologie, Universität Innsbruck, Innrain 52, A-6020 Innsbruck, Austria. Fax: 0043-507-2914; e-mail: Diethard.G.Sanders@uibk.ac.at

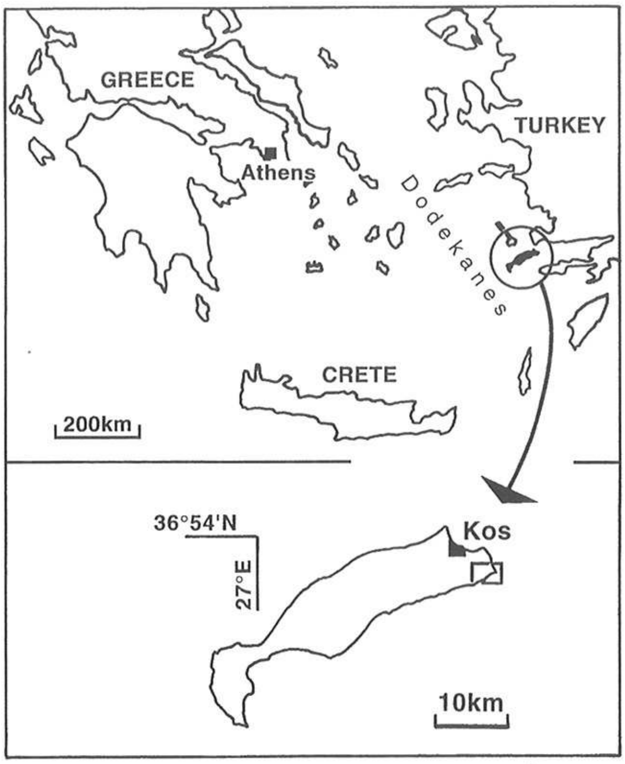


Fig. 1. Geographic position of Kos island. Kos city is situated at the northeastern end of the island. The rectangle delimits the described coastal sector.

Holocene gravelly beaches may show significant changes in morphology and grain size distribution over a period of a few years (Kirk 1980), yet observations on the short-term and medium-term changes of gravelly beaches are very rare (Hart & Plint 1995). Since gravel beaches are often associated with rocky shores, it may be expected that there exist beaches with features transitional between gravelly beaches and rocky shores. On the island Kos in the Aegean Sea, a lateral change from a cliff shore via a „coarse-clastic beach" into a gravelly beach was observed. In addition, the changes of the gravelly beach during and after two high-energy events were observed, by coincidence, during a stay in fall 1996. The observations are relevant to the dynamics of gravelly beaches and to the facies interpretation of fossil transgressive successions.

2 GEOLOGICAL SETTING

Kos island is part of the Dodekanes archipelago (Fig. 1) situated atop the Central Hellenic nappe system, a stack of nappes thrust top-south during the Early Tertiary. Subsequent to Neogene extension, today the Dodekanes rise from a shelf that is interspersed with shallow basins (Bernoulli et al. 1974; Jacobshagen 1986, and references therein). The back-bone of Kos, the Dikeos range, consists in its western part of two stacked, Upper Paleozoic series mainly of metapelites, metapsammites and marbles. The Paleozoic rocks are overlain along a thrust by a Lower Cretaceous to Middle Eocene succession of deep-marine deposits (Wachendorf & Gralla 1983). The eastern part of Dikeos range is separated by a normal fault from the western part, and consists of a series more than 600 m thick of metamorphic flysch („Thermi flysch" Auct.) with olistoliths that consist of mainly of marble, metabasalt, chert, conglomerates and breccias (Wachendorf & Gralla 1983). The southern flank of Dikeos range, and the main part of the southern coast of Kos consist of steep slopes and rock cliffs.

At the northern flank of Dikeos range, Eocene shallow-marine deposits (Bignot & Guernet 1976) are overlain by an Upper Miocene succession that, in the considered area, consists mainly of volcaniclastics (dated at 10.6 Ma b. p.; Altherr et al. 1976), lacustrine carbonates, lacustrine marls and cherts (Vasilios unit; Böger et al. 1974) (Fig. 2). The Vasilios unit is overlain by a succession a few tens of meters thick of spring tufa, lacustrine carbonates and marls (Palioskala unit; Böger et al. 1974; Willmann 1983). The Vasilios unit and, locally, the Palioskala unit are overlain by Pliocene fluviatile conglomerates, sands, marls, and clays (Phokas unit). The Phokas unit is overlain by Quaternary alluvial deposits and by hillslope colluvium (Böger et al. 1974; Willmann 1983) (Fig. 2).

Plate 44 Different beach sectors, NE part of Kos island, Aegean Sea.

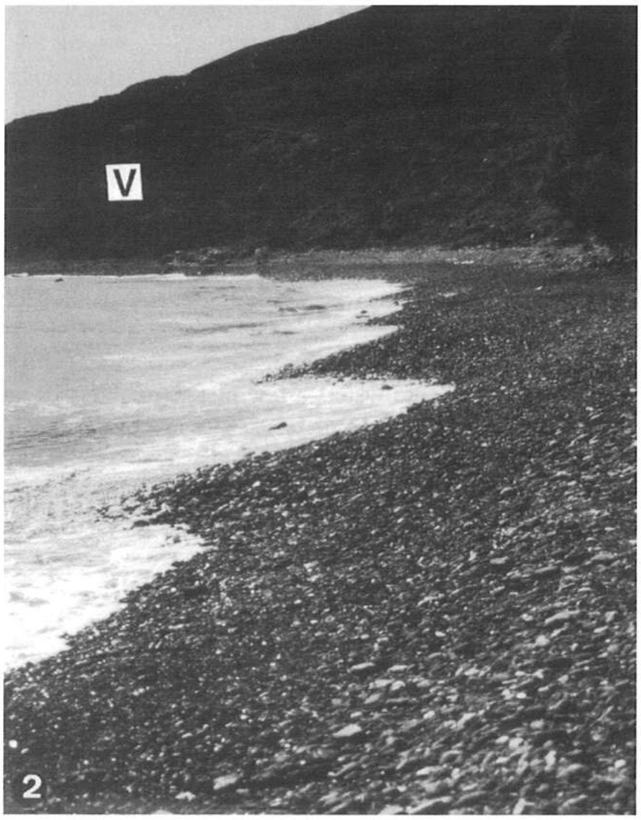
Fig. 1. Coarse-clastic beach ("Thermi beach") of subangular to well-rounded, prolate to oblate cobbles to boulders arranged in seaward-dipping imbricated fabrics. Look to southwest. The large boulder on the left side is an olistolith of marble derived from the cliff succession. Towards southwest, in the background of the photo, a rocky shoreline with boulders and plunging cliffs starts ("Empros beach").

Fig. 2. Gravelly beach ("Dimitra beach") along an Upper Miocene succession (Vasilios unit, labelled V). Look to southwest. Dimitra beach shows small beach cusps flanked by projecting ridges of gravel. Towards the southwesternmost part of this beach, the gravel ridges disappear, and the beachface is straight. Note oblique wave approach.

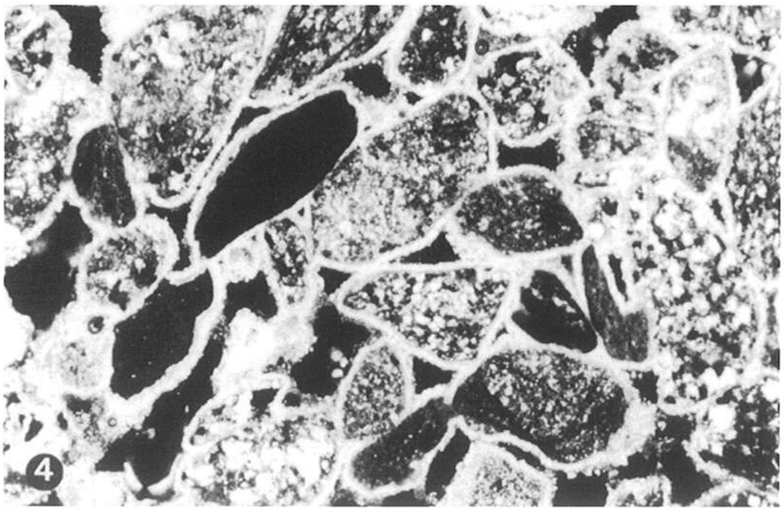
Fig. 3. Gravelly beach ("Phokas beach"), viewed towards northeastern limit of the considered coast at Cape Phokas. Towards Cape Phokas, the gravelly beach becomes narrower, and pinches out into a rocky shore. In its central part, Phokas beach is characterized by a backshore up to 20 m wide, and a more or less flat, uniform beachface composed of fine gravel to coarse sand. Note oblique wave approach.

Fig. 4. Thin section photomicrograph of fine-grained, well-sorted conglomerate composed mainly of metapsammites from the "Thermi flysch", and of a few volcaniclastic rock clasts. The clasts are coated by an isopachous fringe of radial-fibrous calcite cement. Crossed polars. Backshore of Phokas beach. Sample Ko 1. Width of view 10.5 mm.


1


V
2


3


4

3 METHODS

The beach was practically continously observed over a period of two weeks, from September 23rd to October 7th, 1996. During swell and fairweather wave conditions, the shoreface was explored by snorkeling. Eleven sediment samples from the beachface to shoreface of „Dimitra beach" (see chapter 5) were studied under the binocular. From a portion of each sample, lithic clasts and bioclasts were separated quantitatively. Thin sections of gravels and of a lithified beachface conglomerate served for documentation of beach clasts. Because the described beach changes were not observed as part of a campaign planned in advance, the investigations had to be made by simple methods, with basic field geologic equipment.

In the field, the size of gravels to cobbles was determined by visual estimation checked by a few measurements in each case. A simplified Wentworth size classification was applied. „Fine gravel" here corresponds to both the very fine gravel and fine gravel of the Wentworth scale, „medium gravel" to the medium gravel of the Wentworth scale; „coarse gravel" correlates with both coarse and very coarse gravel of the scale. Rounding and sorting of gravels were estimated visually in the field. The estimates of rounding and sorting were subsequently re-checked, from numerous photographs, by means of comparators. For rounding and sphericity, the comparator of Pettijohn et al. (1987) was used. For sorting, the comparators of Longiaru (1987) were applied. Field determination of sand grain sizes was made by inspection with hand lens of dried sand strewn onto printed graph paper pad. Because of the comparatively low resolution of this method, a simplified Wentworth scale of grain size was applied: „fine sand" here includes both very fine and fine sand, „medium sand" corresponds to medium sand of the Wentworth scale, and „coarse sand" includes both the coarse sand and very coarse sand of the scale.

In the harbour office of Kos, neither tide gauges nor wind track and wind intensity roses were available. A negligible tidal range was documented by measuring, with a dipstick, the distance from water level to the brink of a wooden jetty situated close to the northeastern end of Dimitra beach. Despite some imprecision of such a measurement because of waves, on several days the sea was practically flat, allowing for measurement within about 10 cm of precision. Moreover, no significant lunar component of tidal range was indicated during the two weeks of observation. An insignificant tidal range is further supported by a very narrow intertidal epibiontic overgrowth along rocky shores. Wave period was measured by stopwatch as the time interval between the plunging of breakers. The description of the two storm events is a shortened version of a protocoll taken in the field. The arrangement of the plates is largely adapted to the description of storm/post-storm changes (see below).

4 BEACH SECTORS

The shelf in front of the considered coastal sector (Fig. 2) slopes steeply; the 100 m-isobath is situated about 750 m offshore (Sheet No. 613, Bundesamt für Seeschiffahrt & Hydrographie 1997). During observation time, tidal range on the considered coastal sector was less than a decimetre. The southern and western shore of Kos consist of rock cliffs and, subordinately, of gravelly beaches and sandy pocket beaches. No fluvial input of sand and gravel takes place. In the considered area, different shore sectors illustrate a lateral change from a rocky shore to a gravelly beach (Fig. 2).

The southwesternmost beach sector, „Empros beach", is part of a long rocky shore on the southern side of Kos. Empros beach shows steeply inclined to overhanging cliffs that plunge down into waters a few meters to about 10 m deep; there, the cliffs are onlapped by a submarine, steep apron of boulders. Local, short pocket beaches of cobbles to small boulders grade into a submarine apron of cobbles to boulders that slopes down to 5-10 m of water depth. Towards northeast, the pocket beaches become longer, and Empros beach grades into the adjacent "Thermi beach" (Figs 2, 3A). Landward, Thermi beach is bounded by a steep slope to cliff based by local aprons of extremely poorly sorted angular gravels to boulders. Thermi beach is up to about 10 m wide, and consists mainly of subangular to well-rounded cobbles to small boulders (Pl. 44/1). The clasts are arranged in

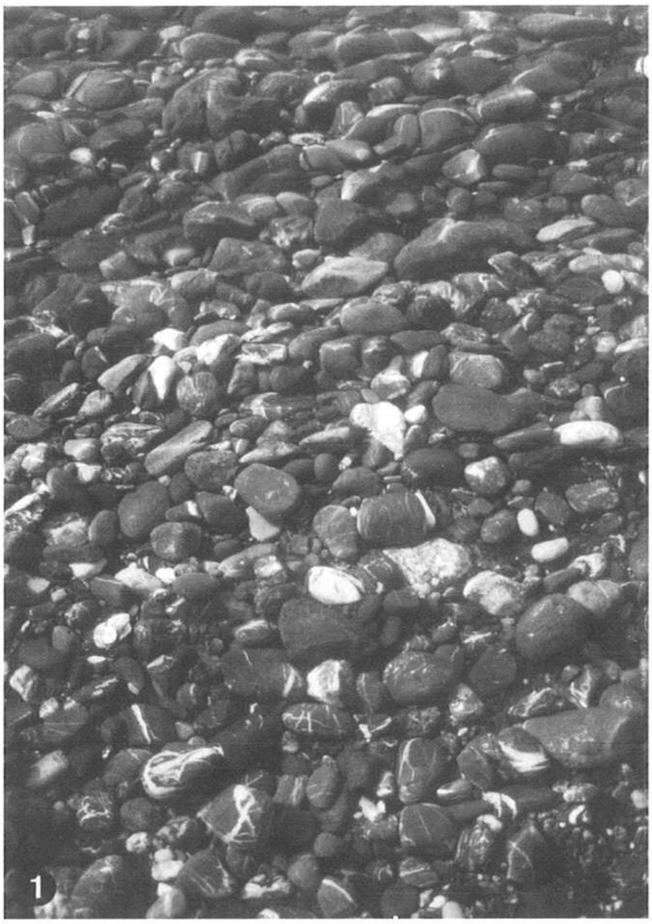
Plate 45 Features of Dimitra beach (Kos island, Greece) before and after high-energy event.

Fig. 1. Bottom of well-rounded coarse gravels to cobbles, seen seaward. This veneer extends from the fairweather plunge step (cf. Figs. 3, 4) into water about 0.8-1.3 m deep. Note the unencrusted surface of the clasts, the moderate sorting, and the paucity of sand. Width of view about 0.8 m.

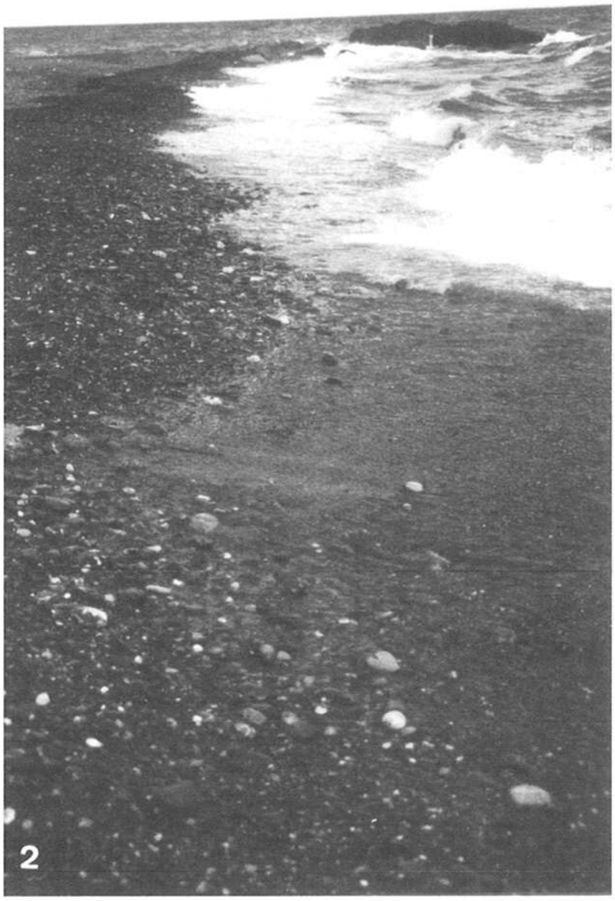
Fig. 2. Northwestern end of Dimitra beach, during rise of a weak storm. The formerly cuspate fairweather beachface with gravel ridges (cf. Pl. 44/2) became flattened and widened.

Fig. 3. Central part of Dimitra beach after weak storm, during waning swell. Maximum storm wave uprush indicated by accumulations of uprooted sea grass (arrowtips) and a small, indistinct step. During decreasing swell, gravel ridges started to develop. Within the small beach cusps defined by the gravel ridges, the floor was paved by gravel of similar grain size than the gravel of the ridges. Beach shown at maximum swell wave uprush.

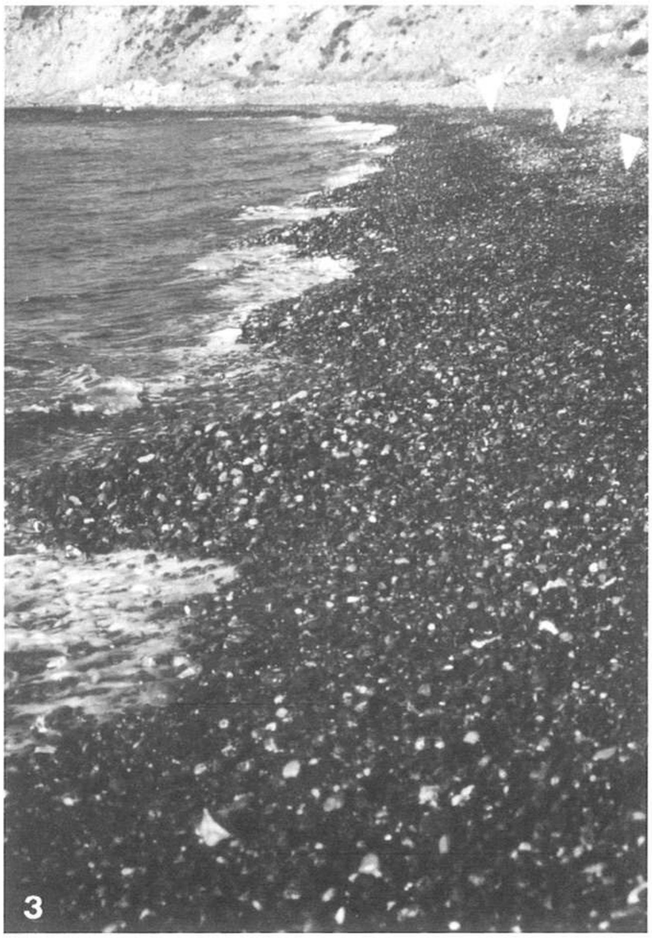
Fig. 4. Central part of Dimitra beach during waning swell, but at a more advanced stage than shown in Pl. 45/3. Beach cusps delimited by gravel ridges had re-developed. The upper limit of wave uprush is marked by a small morphologic step (dashed white line). The crest of each gravel ridge (marked by arrowtips) strikes oblique relative to general strike of the shoreline. In the foreshore between gravel ridges, a veneer of fine gravel to coarse sand developed that contains, near its landward end, scattered medium gravels to small cobbles. Note slightly oblique approach of swell. Shoreline sector shown is about 15 m long.



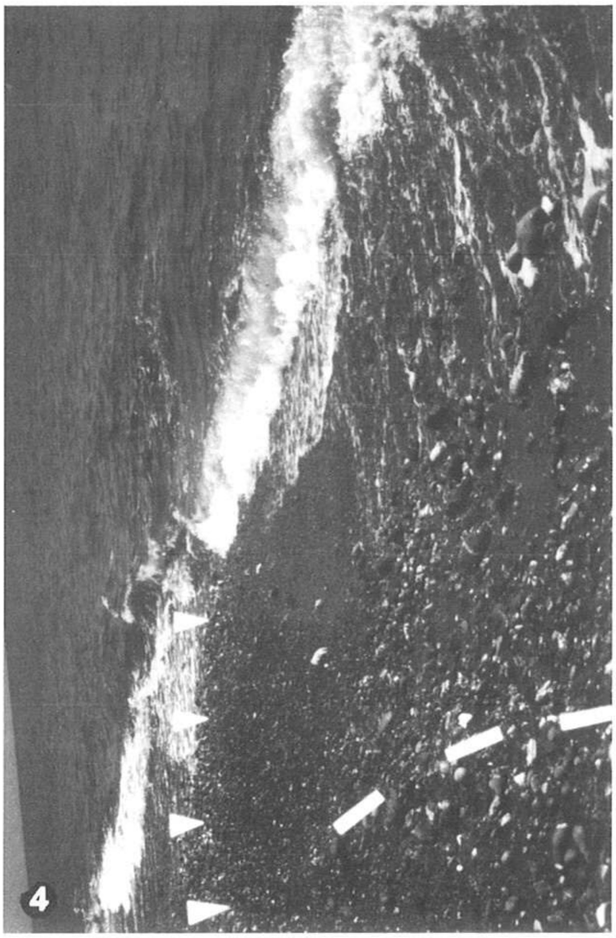
1



2



3



4

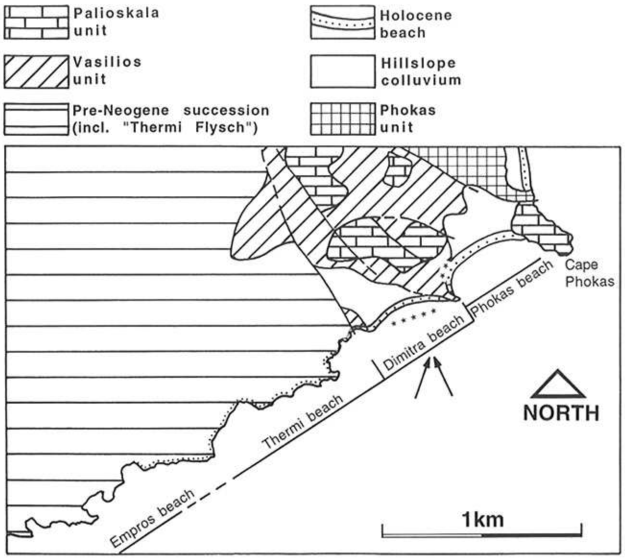


Fig. 2. The eastern part of the area consists of a pre-Neogene succession dominated by metapelites and metapsammites, with intercalated olistoliths. This succession is separated by a fault from an Upper Miocene to Pliocene succession that consists mainly of volcaniclastics (Vasilios unit), of lacustrine carbonates, marls and chert (Palioskala unit), and of a succession of marls, sands, and conglomerates (Phokas unit). These units are overlain by Quaternary alluvial deposits and, mainly, of hillslope colluvium that is onlapped by the Holocene beach (modified from Böger et al., 1974). The considered coast is subdivided into distinct beach sectors. Along Phokas beach and in the subtidal environment in front of Dimitra beach, erosional remnants of a lithified Quaternary gravelly beach succession are present (small asterisks). The two black arrows show storm wave approach during the period of observation.

seaward-dipping imbricated fabrics that, depending on mean clast size, sorting and rounding may be more or less developed. Gravelly pocket beaches typically consist of well-rounded, medium to coarse gravels to cobbles. The pocket beaches have a narrow, steep beachface limited seaward by a poorly developed fairweather plunge step. Seaward of the shoreline, a slope of subrounded to well-rounded cobbles to small boulders, with admixed angular to subangular clasts, grades into waters a few meters deep. Olistoliths and cliff boulders from the Thermi flysch are scattered ahead of the cliffs (Pl. 44/1). The uppermost shoreface is characterized by submerged/partly submerged boulders covered by sea grass, by cobble to boulder veneers partly covered by sand and sea grass, and by sand flats and sea grass meadows. In waters a few meters to about 10 m deep, the slope becomes more gentle, and the gravel to boulder substrate becomes interspersed with submarine sand flats and sea grass meadows. Northeast of the fault between Thermi flysch and Vasilios unit (Fig. 2), a distinct change in beach morphology occurs.

Along the southwesternmost part of the adjacent „Dimitra beach" (Fig. 2), the Vasilios unit forms a cliff about 10 m high (Pl. 44/2), yet the beach gravel spectrum is strongly dominated by clasts from the Thermi flysch. Gravels from the Vasilios unit are subordinate in abundance even in the most landward fringe of the beach; a few meters seaward, in the active beachface, these clasts are very rare. To northeast, hillslope colluvium makes up the immediate hinterland of the beach (Fig. 2). Dimitra beach is characterized by small cusps each flanked by ridges of gravel and centered by a foreshore sand flat (Fig. 3B; Pl. 45/4). In the shoreface ahead, submerged rock ridges and boulders are present that consist of a stratified conglomerate composed of well-rounded, fine to coarse gravel (asterisks in Fig. 2). The changes of Dimitra beach during and after two storms are described in chapter 5.

From hinterland to shoreline, Phokas beach (cf. Fig. 2, Pl. 44/3) shows a backshore of sand with floating subangular to rounded gravels to cobbles, a belt rich disc-shaped gravels to cobbles, and a gentle runnel paved mainly with disc-

Plate 46 Features of Dimitra beach (Kos island, Greece) during and after high-energy event.

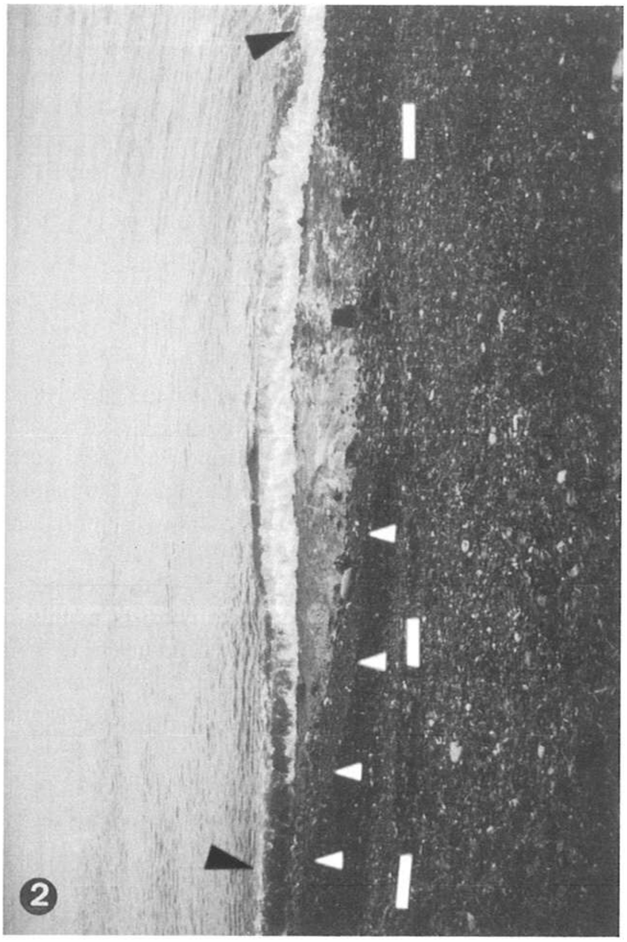
Fig. 1. Central part of beach during early waning of a moderate storm. The storm beachface is a relatively plane, more or less uniform surface about 6 m wide without gravel ridges and foreshore sand flats (cf. Pl. 44/2 and 45/4). On the beachface, sand to small boulders are moved to and fro; no segregation of clast sizes and shapes occurs. Note that storm berm is only poorly developed as a faint, small ridge.

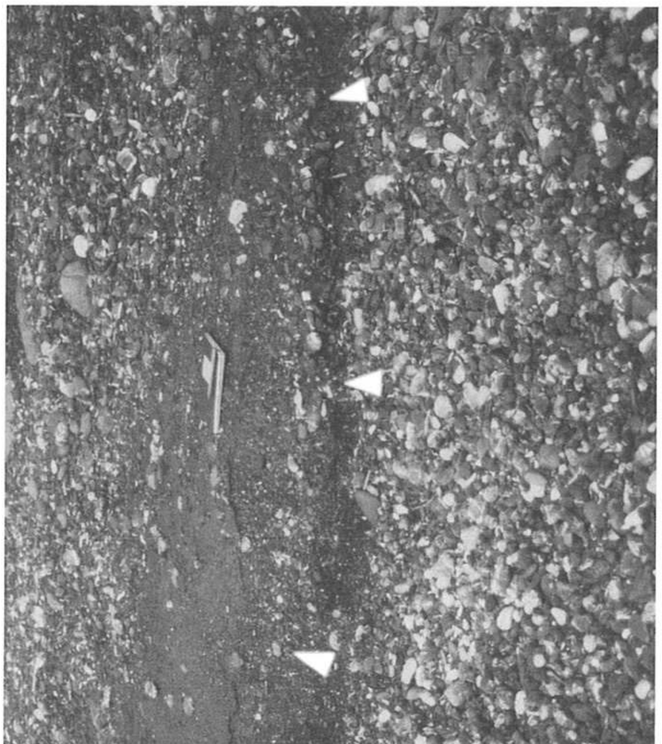
Fig. 2. Early fairweather state after storm effects figured in Pl. 46/1. The landward limit of the poorly developed storm berm is an accumulation mainly of sea grass blades. The seaward limit of the berm is a small step (white lines). Seaward, gravel ridges that strike with their crests (white arrowtips) obliquely relative to overall shoreline strike delimit beach cusps a few meters wide. At their landward fringe, the cusps are paved by very poorly sorted fine gravel to cobbles. In the foreshore part of the beach cusps that is washed by every wave, a veneer of fine gravel is present. Note arcuate shape (delimited by black arrowtips) of plunged wave. Width of view about 6 m.

Fig. 3. Stranded sand flat of early waning stage. The sand flat developed in a relatively high position, and became largely eroded during decreasing swell, and fairweather beach restoration. The sand flat consists of a veneer of medium to coarse sand atop a layer of fine gravel. The layer of fine gravel is underlain by a lense (marked by arrowtips) that consists mainly of imbricated, disc-shaped gravels. The gravel in front of the stranded sand flat is the landward part of a gravel ridge that developed during waning swell. Width of view 2. 4 m.

Fig. 4. Detail from Pl. 46/3, showing imbricated disc-shaped gravels below stranded sand flat. The dip of the imbricated gravels is subparallel to the overall trend of the shoreline. The small scarp was artifically excavated. Pen for scale is 14 cm long.


1


2


3


4

shaped, well-rounded medium to fine gravels (Fig. 3C). The runnel is limited by a gentle berm of very well-rounded, fine to medium gravel. Seaward, the berm grades into the active beachface that consists mainly of very well-rounded, fine to fine medium gravel (Pl. 44/3). Only locally small, poorly developed cusps are present in the uppermost part of the beachface. The beachface is bounded by a fairweather plunge step up to a few decimeters high. Seaward of the plunge step, a substrate of coarse sand to gravel extends for about 10-15 m offshore. In waters 3-5 m deep, submarine sand flats and sea grass meadows appear, and extend offshore at least for hundred meters.

Both along Dimitra and Phokas beach, the gravel spectrum is strongly dominated by metamorphic turbidite sandstones of the Thermi flysch. Metabasalts and cherts of the Thermi flysch are subordinate. Volcanics, lacustrine limestones and cherts of the Neogene succession are only trace components. In the backshore of Phokas beach, erosional remnants of a well-stratified conglomerate are present (asterisks in Fig. 2). The conglomerate consists mainly of moderately well to very well-sorted, subrounded to well-rounded medium to fine gravels coated by an isopachous fringe of radial-fibrous calcite cement (Pl. 44/4). The clast spectrum is closely similar to the recent gravelly beach. The stratigraphic relation of the conglomerate to the substratum is not exposed.

4.1 Discussion

The differences among the described beach sectors are confined to the backshore to upper shoreface, whereas the observed part of the lower shoreface is characterized by a more-or-less uniformly sloping bottom of sand with sea grass meadows. Along Empros beach, the absence of an abrasion platform probably results from both the small tidal range and the silicic metamorphic rocks that are quite resistant to bioerosion, weathering and abrasion. In the geological record, the transgression of such a coast were recorded by a basal, marine cliff talus accumulation that is overlain by lower shoreface to inner shelf deposits (Fig. 4A) (cf. Miller & Orr 1988; Semeniuk & Johnson 1988; Lescinsky et al. 1991; Johnson et al. 1996). Along Thermi beach, features of a rocky shore are the subaerial cliff, the very coarse-grained beach deposits of rounded cobbles to small boulders locally arranged in seaward-dipping imbricated fabrics, the absence of a plunge step, and the large cliff boulders. Probably because of their overall poor sorting and the prevalent coarse gravel to cobble clasts the interspersed gravelly pocket beaches with poorly developed plunge step and seaward clast imbrication are devoid of highly organized morphological features as present on other gravelly beaches (compare Fig. 3B; see chapter 5 below). In the geological record, the transgression of a „coarse-clastic" beach such as Thermi beach were recorded by basal beachface deposits mainly of poorly stratified, coarse gravel to small boulders arranged in seaward-dipping imbricated fabrics. The beachface deposits are overlain by bioturbated/cross-laminated arenites and conglomerates of the shoreface and, higher up-section, by shelf deposits (Fig. 4B). Both Dimitra and Phokas beach do not show features of progradation, such as a marsh and beach ridges (see e. g. Bird 1969, and Randall 1977, for Holocene prograded gravelly beaches; and Massari & Parea 1988, for fossil examples). Both beaches are narrow and sharply abut the older substratum along an erosional contact, i. e. they show a transgressive configuration. Transgression of Dimitra and Phokas beach would produce a basal layer of upper/lower beachface conglomerates, overlain by shoreface conglomerates and cross-laminated and bioturbated shore zone arenites (Fig. 4C) (cf. Bourgeois 1980; Nemec & Steel 1984; Sanders 1996, 1997).

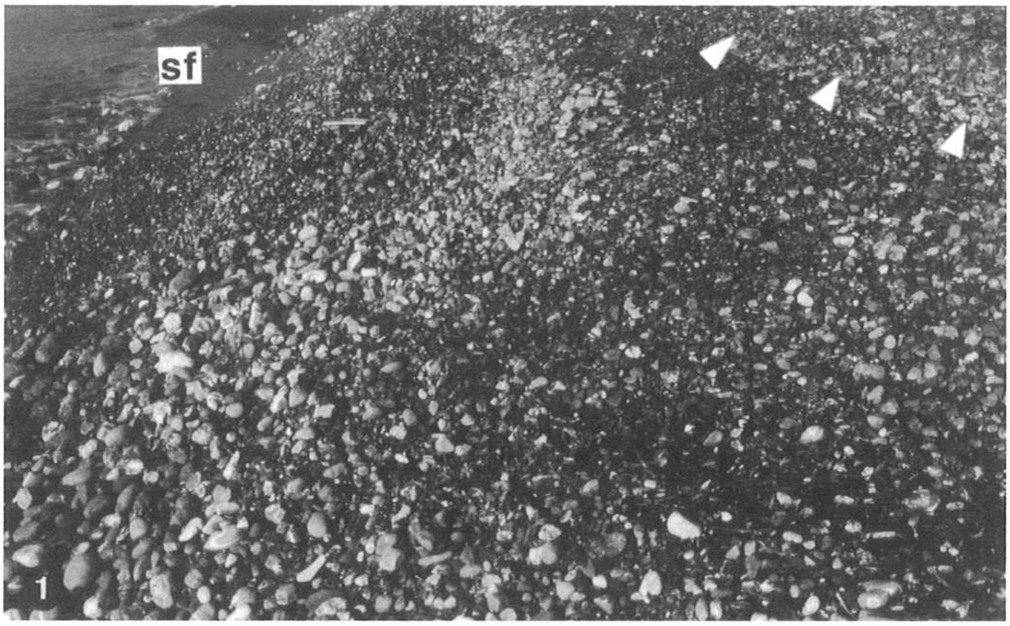
As generally valid for transgressive shore zone successions, the degree of preservation would vary with rate of relative sea-level rise and sediment input. All other factors equal, distinct differences in the thickness of the shoreface and beachface part, and the onset of inner shelf deposits

Plate 47 Features of the waning stage, Dimitra beach (Kos island, Greece).

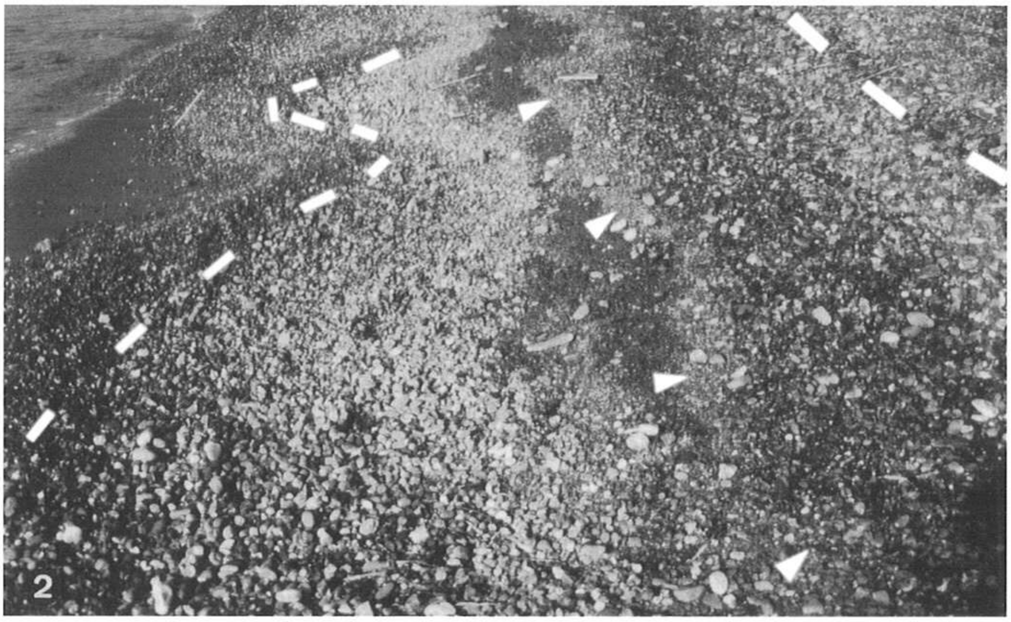
Fig. 1. „Stepped gravel ridge". The most landward, highest part of the ridge (delimited by arrowtips) consists mainly of coarse gravel. The central part of the ridge shows a relatively flat, finer-grained top, but towards its seaward limit consists mainly of coarse gravels. The morphologically lowest part of the ridge is overall finer-grained, and is characterized by a flat top and a steep step towards the adjacent sand flat (sf). Width of view 5 m.

Fig. 2. Stepped morphology, northeast Dimitra beach. The most landward step (white line) marks the limit of storm wave uprush. Seaward, a gently convex ridge 1 (delimited by arrowtips) of poorly sorted fine to coarse gravels is present. In a lower position, an array of obliquely projecting ridges 2 (delimited by dashed white line) shows an overall convex profile, with a subhorizontal top rich in fine gravel to sand (darker strip) and a steeper slope of medium to coarse gravels. To the sea, these ridges are limited by overall finer-grained ridges 3 with a distinct relief. The spacing of the lowest, most seaward ridges 3 follows the spacing of the coarser-grained ridges 2. Note the steep slope (shown by white bar) of the lowest gravel ridges towards the foreshore sand flat. Width of view 5 m.

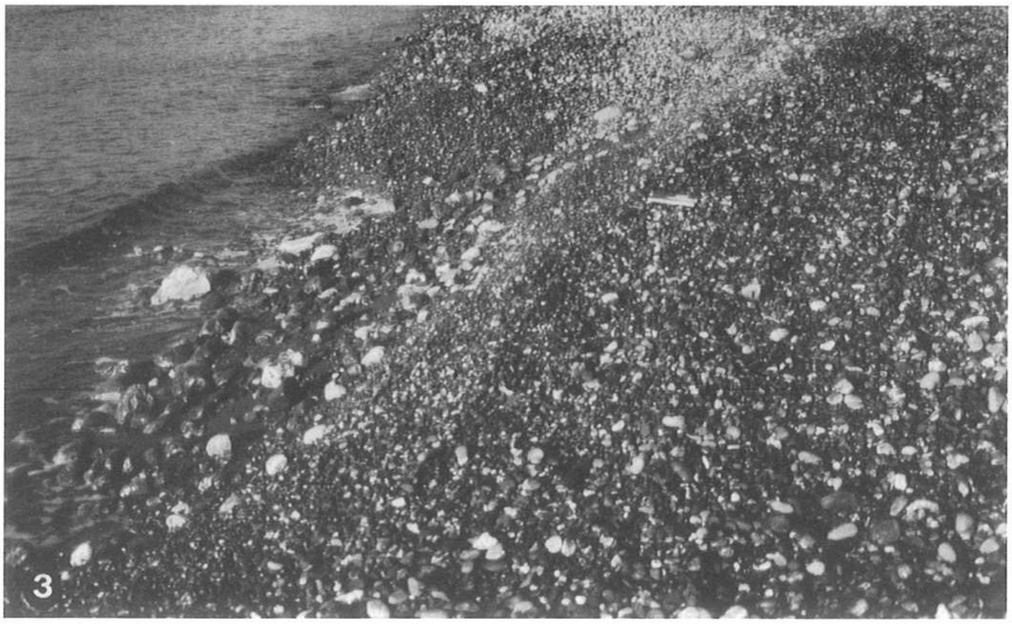
Fig. 3. Central part of Dimitra beach in mature fairweather state. The oblique gravel ridges flank cusps paved by veneers of medium gravels to small boulders that lie scattered on a substrate of sand to fine gravel. In the early fairweather state of the beach, the clast veneers in the cusps were covered by olique-triangular foreshore sand flats (cf. Pl. 46/2 and 47/2). Width of view about 4. 5 m.



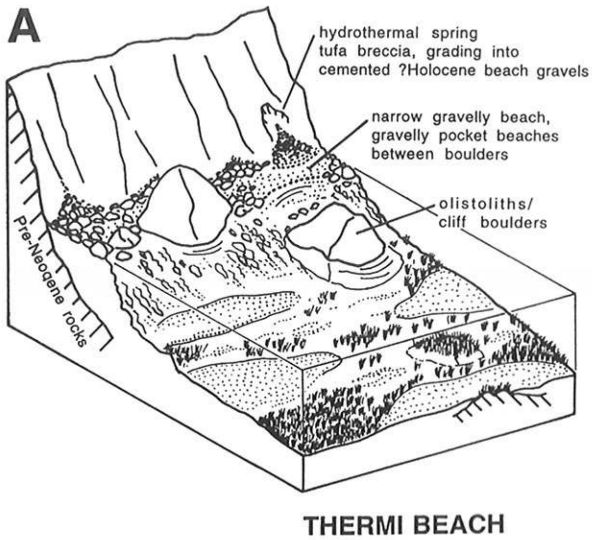
1

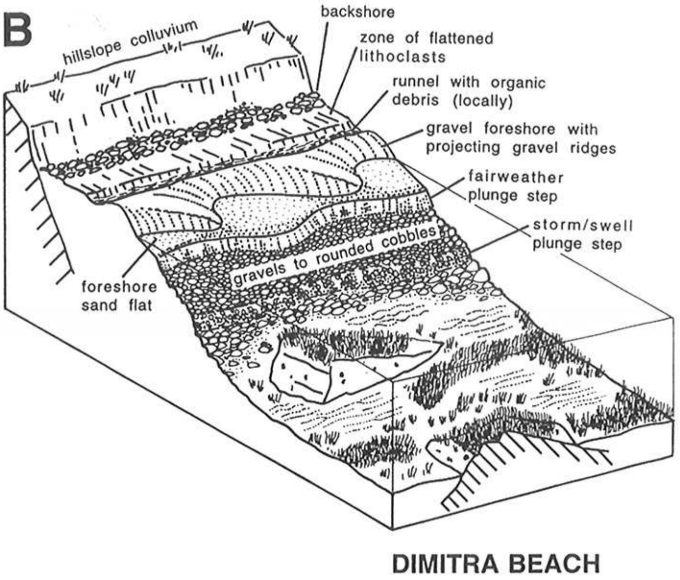


2



3





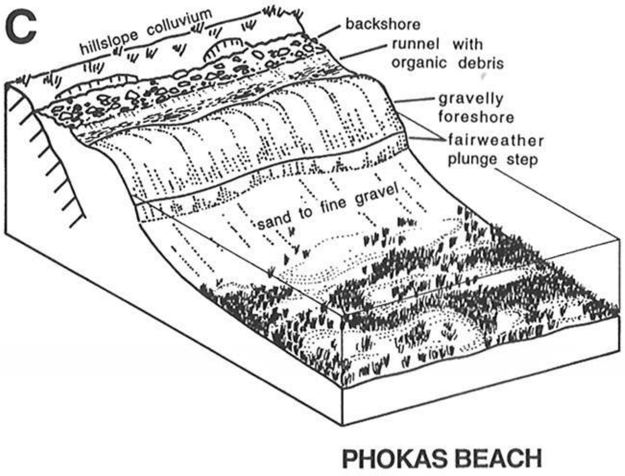


Fig. 3 A. Thermi beach shows a subaerial cliff based by an apron of angular gravels to boulders. Over most of its extent, the beach consists of subangular to well-rounded cobbles to boulders (Pl. 44/1). Locally, gravelly pocket beaches are present between boulders, or between cobble-boulder beaches. The uppermost shoreface is a steep slope of rounded cobbles to boulders. Along the beach, boulders up to a few tens of meters in size derived from the Thermi flysch are scattered. The upper shoreface environment is characterized by submerged or partly submerged boulders colonized by sea grass, by cobble to boulder veneers that are partly covered by sand and sea grass, and by sand flats locally covered by sea grass meadows.

3 B. Dimitra beach, shown in an early fairweather configuration (see Pl. 44/2, 45/4, 46/2). Hillslope colluvium abuts a backshore of subangular to well-rounded coarse gravels to small boulders. Seaward, a belt of disc-shaped, medium to coarse gravels, a gentle runnel, and an array of small beach cusps are present. Each cusp is delimited by gravel ridges aside of a foreshore sand flat of oblique-triangular shape. A fairweather plunge step delimits both the sand flats and the seaward end of the gravel ridges. Seaward, a veneer a few meters wide of well- to very well-rounded gravels to cobbles is bounded by a storm/swell plunge step. The upper shoreface is characterized by wave-rippled to bioturbated sand flats locally covered by sea grass meadows, and by rock ridges and boulders of a lithified Quaternary beach conglomerate.

3 C. Phokas beach. Hillslope colluvium abuts a backshore of sand with scattered subangular to well-rounded gravels to cobbles. Landward of the storm berm, a gentle runnel rich in sea grass blades is present. The beachface consists mainly of fine gravel, and is a more or less even surface bounded seaward by a fairweather plunge step. The uppermost fairweather shoreface is veneered by fine gravel to sand, but coarse gravels to cobbles are present near the eastern and western end of the beach. Seaward, the shoreface consists mainly of sand flats locally covered by sea grass meadows.

above base of section (cf. Fig. 4) largely result from marked differences in the actual morphology of each beach sector. In the geological record, intervals deposited from transgressive rocky to gravelly shore zones may show marked lateral variations of thickness, mean clast size, sorting and rounding, and sedimentary structures, as characteristic of transgression onto substrata with a differentiated erosional morphology (Sanders 1998). Thus, sections that may suggest „rapid" sea-level rise (Fig. 4A) may accumulate laterally adjacent to contemporaneous sections suggesting a more „gradual" rise (Fig. 4C).

The ridges and boulders of conglomerate in the shoreface of Dimitra beach, and the conglomerate back shore of Phokas beach represent erosional remnants of a Quaternary gravelly beach. The isopachous radial-fibrous cement of the conglomerate is identical to magnesian calcite cement as common in Quaternary Mediterranean beachrocks (cf. Alexandersson 1972). The recent beach gravels thus are either derived from reworking of older beach conglomerates, and/or from transgressive coastal erosion of the older substratum. The dominance of clasts of pre-Neogene metamorphics both in the older conglomerate and in the recent beach sediment reflects the large outcrop area of the series and its high content of lithologies quite resistant to abrasion. In the following, the fairweather configuration and two cycles of storm/post-storm changes of Dimitra beach are described. Dimitra beach was chosen because of its well-developed morphological features and zonation as compared to the other coastal sectors (Fig. 3), and because it showed the most distinct storm/post-storm changes in beach configuration.

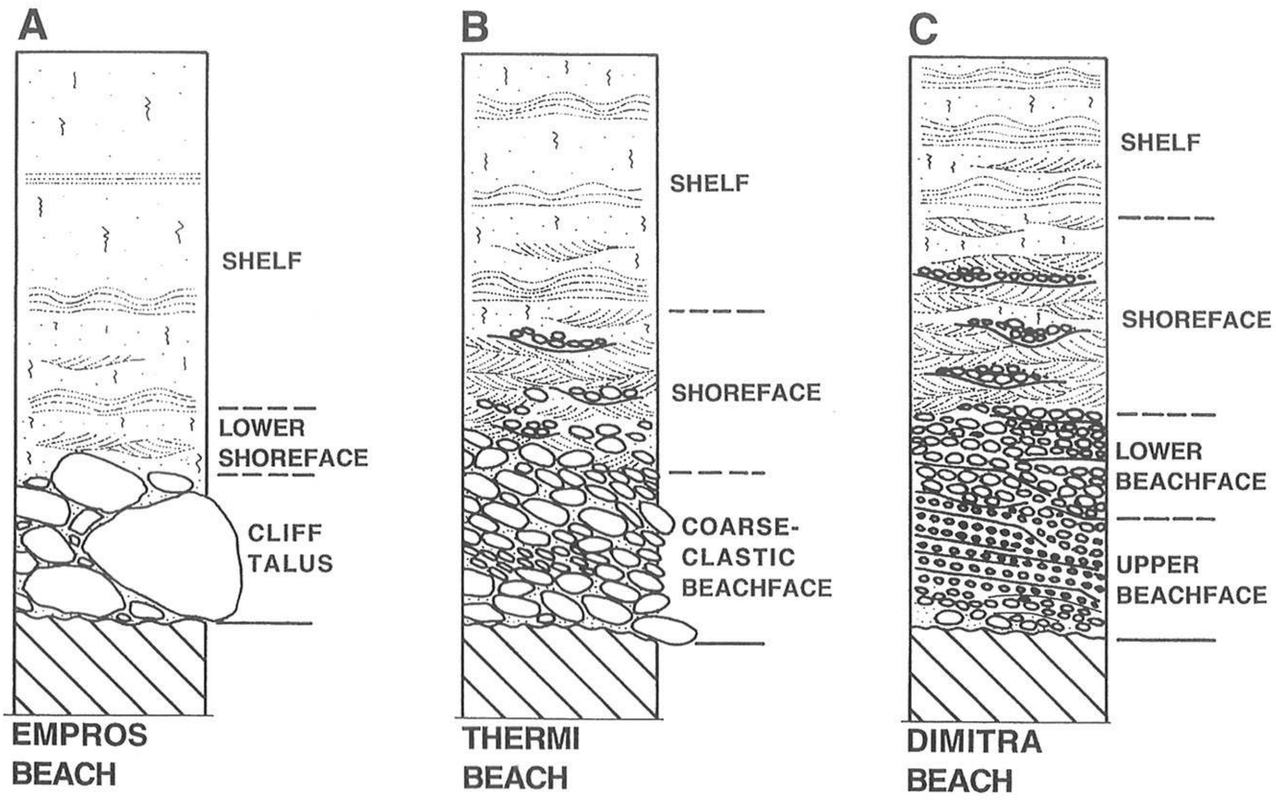


Fig. 4. Hypothetical, contemporaneous transgressive successions from different beach sectors as described (cf. Fig. 3). A: Transgression of a rocky shore were recorded by cliff talus that is followed up-section by lower shoreface to inner shelf deposits. B: Transgression of a „coarse-clastic beach" were based by beachface deposits mainly of poorly stratified, coarse gravel to small boulders arranged in seaward-dipping imbricated fabrics. The beachface deposits are overlain by bioturbated/cross-laminated arenites and conglomerates deposited in the shoreface and, higher up-section, by shelf deposits. C: Transgression of a gravelly beach were based by well-stratified upper beachface conglomerates (with seaward-dipping bedding) and by less distinctly stratified, more coarse-grained lower beachface conglomerates. Above, bioturbated/cross-laminated arenites and conglomerates that accumulated in the shoreface were overlain by inner shelf deposits.

5 DIMITRA GRAVEL BEACH

Along Dimitra Beach, during fairweather conditions a specific set of features was observed (Fig. 3B). The landward limit of the backshore is the erosional contact to the rock cliff or to hillslope colluvium. The backshore consists of poorly sorted medium gravel to small, rounded blocks up to about 40 cm in size. According to local people, this zone is reached by wave uprush only during heavy winter storms. Seaward, a berm 2-4 m wide paved by disc-shaped, medium to coarse gravels is present. The berm locally is bound by a gentle runnel rich in sea grass blades.

Seaward of the runnel, a belt of „gravel ridges" and intercalated, oblique-triangular „sand flats" is present (Figs. 3B, 5). Each sand flat is up to about 10 cm thick, and is underlain by gravel. From the sand flats' upper ends to the plunge step, the sand typically coarsens from medium sand to a coarse sand to coarse sand-fine gravel adjacent the plunge step (Fig. 5). Under persistent fairweather conditions, the sand flats typically are small and interspersed with gravel (see below). In the sand, the total amount of bioclasts is far less than 1% up to about 0.2%. The bioclastic fraction is dominated by abraded and fragmented tests of Elphidiidae. Miliolids, peneroplids, and fragments from molluscs, echinids, crustaceans and bryozoans are present in traces.

At their landward end, the gravel ridges either merge towards a step that delimits the zone of flattened lithoclasts (Fig. 5), or show one or two "steps" built by gravel ridges in a morphologically higher position (Pl. 47/1, 2; see description below). Towards the shoreline, the relief of the gravel ridges becomes more accentuated (Pl. 47/3). In their morphologically higher, landward part the ridges consist of very well-rounded coarse gravels to small cobbles (Fig. 5) arranged in seaward-dipping imbricated fabrics (Pl. 47/1). Towards their seaward end, the gravel ridges consist of moderately to well-sorted, very well-rounded, medium to coarse gravel. Flattened clasts are arranged in steeply (50-80°) seaward-dipping imbricated fabrics. The seaward limit of the gravel ridges is a step (40°-50° steep) situated with its lower part within the zone of fairweather wave uprush. In the beachface gravels, a few shells of Littorinidae and of small Conidae are present. In addition, cerithiaceans, small Tritonidae and Patellidae were rarely found. Other bioclasts such as fragments of bivalves, sculps of *Octopus* and fragments of crustacean tests are very rare.

At their seaward side, both sand flats and gravel ridges are bounded by a fairweather plunge step 10-30 cm in height (Figs. 3, 4). In plan view, the plunge step bows out seaward were it is situated in front of a sand flat, whereas it curves towards a more landward position in front of a gravel ridge

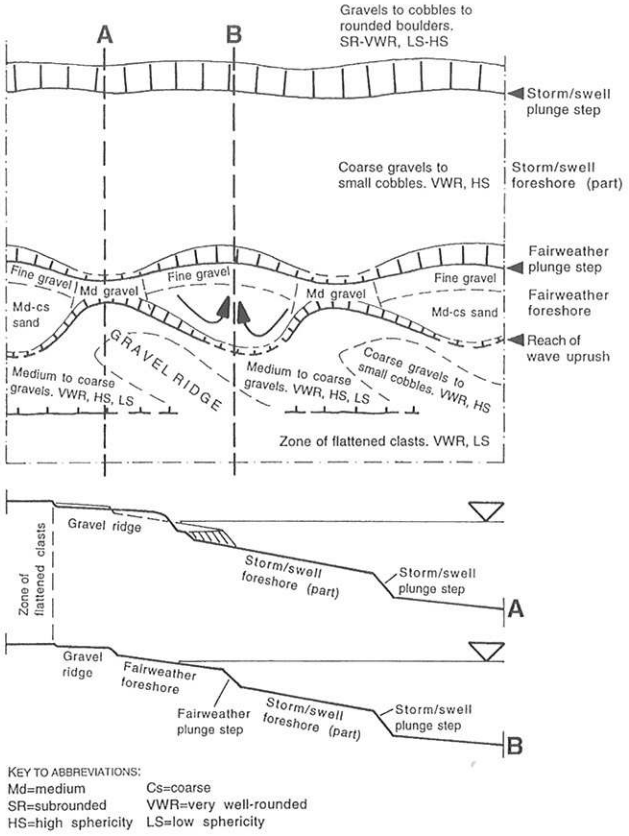


Fig. 5. Above: Plan of morphology and surface sediments in the central part of Dimitra beach, shown in an early fairweather configuration (approximately to scale). In their central part, the gravel ridges consist of coarse gravel to small cobbles, whereas the flanks of the ridges are built mainly by medium to coarse gravel. The curved black arrows indicate the direction of wave uprush and the confluence of backwash on the foreshore sand flat. Below: Along section A, the beach profile consists of the gravel ridge, a narrow beachface mainly of medium gravel, and an indistinct fairweather plunge step. For comparison, the morphology of the laterally adjacent foreshore sand flat is also shown. Along section B, the profile shows the more gently inclined foreshore sand flat bounded seaward by a well-developed fairweather plunge step. The morphology of the fairweather beach appears to be independent from the morphology and the configuration of the storm/swell plunge step farther seaward.

(Fig. 5, Pl. 46/2). The plunge step thus follows the spacing of the gravel ridges and the sand flats. Seaward from the plunge step, a veneer some meters wide of moderately sorted, medium to coarse gravels to cobbles with a few small boulders up to about 30 cm in size is present (Pl. 45/1). The gravels to cobbles are well- to very well-rounded and typically of high sphericity. The surface of the gravels is smooth to nearly polished, and is devoid of epibionts. This veneer extends to a water depth of about 1 m, where it is again bounded by a morphological step (Fig. 5) that developed near the plunging point of breakers during storm to swell conditions (see chapter 6).

Seaward of the storm/swell plunge step, a belt up to more than 10 m wide of moderately to poorly sorted, medium gravels to small, subrounded boulders up to 1 m in size is present (Fig. 5). The gravels to boulders are covered by algal mats about 1-3 mm thick (rich in baffled sand, silt and particulate organic matter) and scattered specimens of *Acetabularia*. At the lower flanks of the clasts bryozoans, serpulid tubes and small red algal crusts are present. In waters a few meters deep, the gravels to boulders become interspersed with patches of sand that, down from about 4-6 m of water depth, grade seaward into a sand flat. The sand patches between the clasts are covered by wave ripples that locally are disrupted by burrows. Near the landward limit of the sand flats, the bioclastic fraction (<< 1% up to about 0.5%) in the sand is dominated by tests of Elphidiidae; peneroplids, fragments from molluscs, echinoderms, bryozoans and crustaceans are accessory. The mentioned submerged ridges and boulders of Quaternary beach conglomerates are covered by meadows of green algae and *Thalassia*. Locally, demosponges are present.

The subtidal sand flat bears patches of sea grass, green algae and demosponges, and is more or less bioturbated. The bioclastic fraction (about 0.1% to 1%) of the sand is dominated by Elphidiidae, but other bioclasts also are common, typically *Peneroplis*, a few miliolids, tri- and biserial textularids, microgastropods, serpulid tubes, bryozoan fronds, and fragments from echinids, bivalves and gastropods. This sand flat extends to at least 10-15 m of water depth, out to approximately 100 m offshore.

6 BEACH CHANGES

6.1 First storm/post-storm cycle

At the start of observations, Dimitra beach was in the fairweather condition as described. During afternoon of September 23rd, 1996, a southeasterly wind built up and reached strong gale to weak storm strength (estimated at 7 to 8 Beaufort) until the evening. During both wind upbuild and fully developed storm, the waves approached from south to southeast (Fig. 2). Shortly before breaking, the waves were about 1 meter high.

During wave upbuilding in the afternoon, the beach gravel ridges became eroded, and the foreshore sand flats vanished. A beachface a few meters wide with a lower slope than the fairweather beachface developed (Pl. 45/2). Within a breaker zone 2-4 m in width, plunging breakers rapidly collapsed and rushed up the gravelly beachface. The distance between the plunging point of breakers to the uppermost reach of wave uprush ranged from 4 to 6 meters. The beachface dipped at about 15°. Until 11 p.m., the waves approached from ESE, oblique to the strike of the coast. These conditions remained until the morning of September 24th. From the morning to about 2 p.m., the wind diminished to a gentle breeze, and wave approach turned to south. In the early afternoon, swell waves 30-40 cm in height (immediately before plunging) approached. In the southwesternmost part of Dimitra beach, the flattened, wide storm beachface had disappeared, and the more or less straight, narrow and steep fairweather gravel beach was in part re-established. In the central and northeastern parts of Dimitra beach, incipient gravel ridges with regular spacing had re-formed (Pl. 45/3).

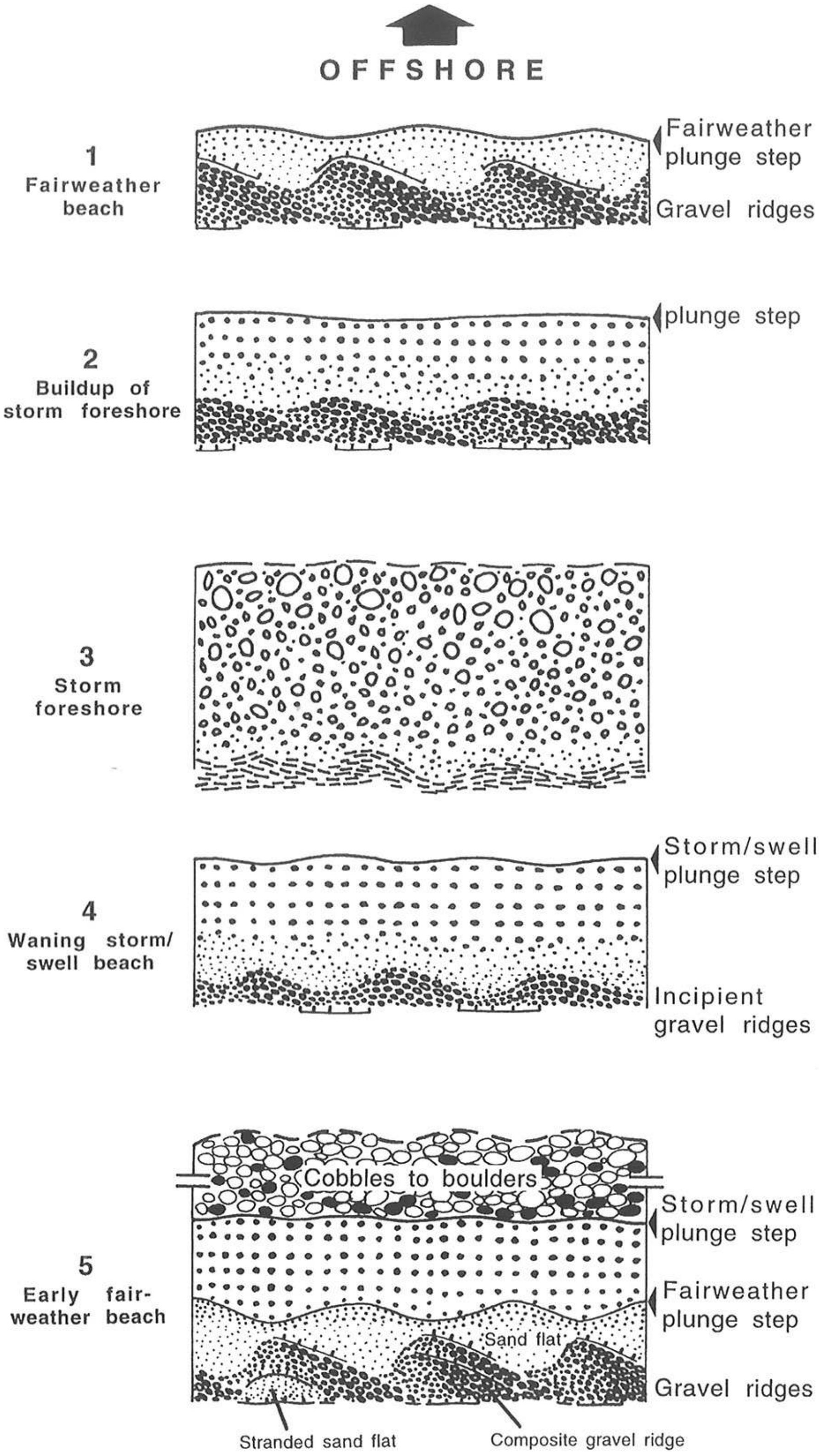


Fig. 6. Storm/post-storm cycle on Dimitra beach. 1: Fairweather configuration (cf. Figs. 3, 5). 2: Storm buildup. Gravel ridges flanking the beach cusps are eroded, fairweather plunge step is destroyed, and the beachface flattens and widens. In the early stage, a more or less straight plunge step is present. 3: Full storm. The beachface dips at about 15°. On the storm beachface, sand to small boulders are moved to and fro by traction and saltation. 4: Waning stage. In a swell regime, incipient gravel ridges of poorly defined, dull-triangular shape appear in a relatively high morphologic position. The storm/swell plunge step may form or be modified during early waning stage. 5: Under decreasing swell, the fairweather beach is re-stored. The early fairweather beach shows well-developed sand flats. „Stranded sand flats" and „composite gravel ridges" formed during decreasing swell. Seaward of the storm/swell plunge step, scattered subrounded to very well-rounded cobbles to small boulders that are unencrusted and show a smooth surface (black clasts) indicate that during storms large clasts were transported at least out into the uppermost shoreface.

Upon further decrease of wind and swell, oblique gravel ridges and intervening triangular sand flats gradually reappeared (Pl. 45/4), and were well-developed in the evening, when the beach showed all its fairweather features (Fig. 5).

During decreasing swell, the gently curved plunge line of the breakers became more and more „bend“ into more narrow sectors of increasing curvature in plan view. The seaward-convex sectors of the plunge line corresponded to a future foreshore sand flat, the landward-convex sectors to an emerging gravel ridge. As each wave rushed up an increasingly larger distance from the margins towards the central part of the sand flat, a „mini-longshore transport system“ was set up that progressively entrained the sand towards the central part of the flat (Fig. 5). The more powerful wave backwash in the central part of the sand flat, in turn, enhanced the tendency of the next incoming wave to plunge farther seaward than in the marginal parts of the sand flat and in front of the gravel ridges. This gave rise to the sinuous plan view of the plunge step.

Seaward of the plunge step, in the belt of rounded and encrusted coarse gravels to cobbles, both non-encrusted gravels and small boulders up to about 40 cm in diameter were then scattered between the encrusted gravels. In the shoreface, the sand flats were covered by wave ripples, down to a water depth of at least 8 meters. Wave conditions continuously calmed until September 27th to waves with an amplitude of 10-20 cm immediately before plunging. During this fairweather period, the gravel ridges remained stable, the foreshore sand flats gradually diminished in size, and the gravel underlying the sand became increasingly exposed.

6.2 Second storm/post-storm cycle

On September 27th, on from 11 a.m., wind from south to southeast built up and reached storm strength (estimated at 8 to 9 Beaufort) at about 2 p.m. During wave buildup, the gravel ridges were gradually eroded and foreshore widening-flattening occurred (Fig. 6, stage 2). At full storm, the waves approached from the south, i.e. slightly oblique to shoreline strike. At 6 p.m. a storm beachface 6-8 m wide had established that dipped with about 15° (Fig. 6, stage 3; Pl. 46/1). At 8 p.m., wave amplitude immediately before plunging was approximately 1.2-1.5 m. Wave period was measured at 6-7 seconds. In the storm beachface a „carpet“ of gravels to small boulders up to about 30 cm in size was moved by traction and saltation within wave uprush and backwash. Clast movement in the backwash was accompanied by a loud crunch testifying to strong impact. Until 12 p.m., the same conditions as at 8 p.m. persisted. On the morning of September 28th, the beach was in the same storm condition as described. In the central part of Dimitra beach, the scarp along the line of maximum wave uprush retreated by 1-1.5 m the night over.

During the morning, the wind decreased to moderate breeze. Between 1 to 2 p.m., swell waves had a period of 7-8 seconds, and an amplitude of 50-70 cm immediately before breaking; the plunging point was situated 2-3 m seaward from the upper reach of wave uprush. The swell approached subparallel to the beach. From 2 to 3 p.m., incipient gravel ridges developed in a regime of decreasing swell amplitude (Fig. 6, stage 4). At 5 p.m., more or less complete gravel ridges and intercalated, triangular sand flats had re-built (Fig. 6, stage 5; Pl. 46/2). At 5 p.m., the swell waves had an amplitude of 40-50 cm immediately before breaking, and a period of 7-8 seconds. The new gravel ridges were laterally shifted relative to the preceeding.

During waning high-energy conditions, in plan view an increasing „sinuosity“ in the plunge line of breakers and, concomitantly, an increasing „compartmentalization“ of wave uprush and backwash was observed; both processes promoted formation of the gravel ridges and sand flats. The development of sinuosity in the plunge line of breakers was related to establishment of a fairweather plunge step at the toe of the beachface. No evident perturbations from which the increase in sinuosity of the plunge line started could be identified. Compartmentalization of wave uprush/backwash directly corresponded to plunge step formation. Where the plunge step was situated farther seaward, beachface slope was more gentle (profile B in Fig. 5), and the waves plunged earlier as compared to their laterally adjacent parts (see Pl. 46/2). As the kinetic energy of the laterally adjacent wave sectors became dissipated slightly later than that in the most seaward part of the plunge step, wave uprush proceeded at higher velocity along the sides of the sand flats. The backwash, in turn, flowed towards the center of the sand flat (arrows in Fig. 5). Thus, sand was entrained from within the gravel ridges and the lateral parts of the sand flats, and was concentrated by the backwash in the central part of the sand flat.

The night over, the sea calmed to nearly flat in the morning of September, 29th, with waves of 10-20 cm in amplitude. The distance between the wave plunging point and the upper reach of wave uprush was less than a metre on the seaward end of the gravel ridges to 1.5 m on the sand flats. The sand flats were gradually reduced in size during the morning. Some of the sand flats that developed during waning swell were „stranded“ in an elevated position, and were partly eroded during calming conditions. Some of these „stranded sand flats" were bound at the seaward side by a small, scarp-like step that was produced from erosion during the overall retreat of wave uprush (Pl. 46/3). Closely below the sand flat, gravels are present that are arranged in imbricated fabrics that dip either more or less directly offshore or dip strongly oblique to the local shoreline (Pl. 46/4). Locally, „stepped gravel ridges“ developed under decreasing swell (Pl. 47/1). The stepped gravel ridges consisted of a ridge situated at a morphologically higher, more landward position, separated by a small step from one or two more ridges in a lower, more seaward position (Pl. 47/2). In the cobble-boulder veneer seaward of the storm/swell plunge step, scattered, unencrusted cobbles to small boulders were present (stage 5 in Fig. 6). The shoreface sand flats were nearly everywhere riddled by wave ripples.

Very calm wind and sea conditions persisted until October 7th. In this interval of time, the gravel ridges were not further modified. The foreshore sand flats, however, were gradually reduced in size over an interval of three days (Pl.

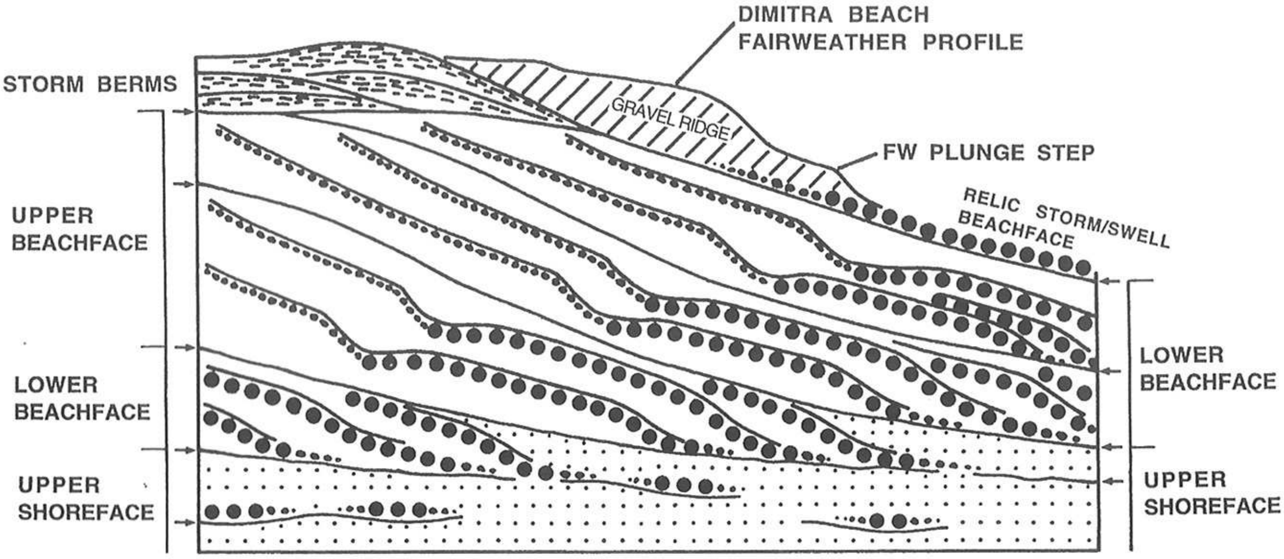


Fig. 7. Scheme of wave-dominated, microtidal prograding gravelly beach (compiled from Massari & Parea 1988, and this paper). The backshore contains storm berms rich in disc-shaped clasts. The beachface deposits are arranged in sigmoidal bedsets vertically separated by master bedding surfaces (marked by small arrows). Upper beachface deposits consist of seaward-dipping strata of well- to very well shape- and size-sorted conglomerates. Steps in bedding may represent fairweather plunge steps. Lower beachface deposits mainly are coarse-grained conglomerates that accumulated in the storm/swell beachface that, however, was substantially modified during each post-storm recovery (see text). In the lower beachface conglomerates, storm/swell plunge steps may be preserved. The fairweather profile of Dimitra beach (cf. Fig. 4, section A) is indicated by the cross-hatched area. Upper shoreface deposits are shown as sand (stippled) with intercalated, erosive-based lenses of shoreface conglomerate.

47/3). After October 2nd, the beach was not subject to further modifications. Until October 7th, most of the wave ripples in the shoreface were obliterated by bioturbation. Only in the uppermost shoreface, wave ripples persisted. After each storm, aside from abundant sea grass blades, entire shoots of green sea grass and of green algae lay astray in the backshore. In addition, sculps of *Sepia*, and a few fragments from crustaceans, and diverse gastropods were littered.

6.3 Discussion

The morphology of gravelly beaches is mainly controlled by mean grain size of the gravel, by the amount of sand present, by wave climate and nearshore currents, tidal range, and rate and type of sediment input (cf. Dobkins & Folk 1970; Kirk 1980; Forbes & Taylor 1987; Hart & Plint 1995). The influence of all these parameters may explain the marked differences in the proposed schemes for vertical development of prograding gravelly beaches (see Bluck 1967; Maejima 1982; Emery & Myers 1996).

On Dimitra beach, the restoration of the fairweather beach during waning high-energy conditions proceeded by size- and shape-sorting of the storm beachface, in feedback with the emergent fairweather beach morphology and sediment distribution. Although probably initiated by some unknown, slight perturbations, the increasing sinuosity of the plunge line of swell waves must proceed in feedback with the laterally adjacent sectors of the same wave, to ultimately arrive at a regular pattern of beach cusps. Because of the negligible tidal range, the „stepped gravel ridges" of Dimitra beach result from the overall decrease in wave height, wave steepness and -energy during the waning stage. The development of the fairweather beach, particularly of the stepped gravel ridges, involves within-shore sorting with respect to clast size and -shape (see Pl. 46/3, 4 and Pl. 47/1, 2). The veneer of moderately sorted, well-rounded coarse gravels to cobbles in the fairweather part of the storm/swell beachface (Pl. 45/1) indicates that this part of the storm beachface was modified during the waning stage by size-and shape-sorting, by onshore transport of smaller gravels (moulded into the fairweather beachface; Fig. 5), and winnowing of sand.

There is no indication for offshore sand transport during fairweather. The sand of the shoreface was carried offshore during high-energy events. The foreshore sand flats at least largely are derived from swell-induced winnowing during beach restoration. Because landward acceleration of the water column from solitary, shoaling waves exceeds the offshore directed one, and since the plunging breakers on Dimitra beach strongly interact with the backwash, the suspended sand in the storm/swell beachface is progressively pushed landward. The reduction in size of the sand flats during fairweather most probably proceeds by entrainment of sand into the underlying gravel framework.

The gravels of Dimitra beach are abraded only during high-energy events. On shorelines, however, that face a large fetch, fairweather waves (e. g. oceanic swells and seas) are nearly always of sufficient energy to induce motion and shaping of beach gravels (see Dobkins & Folk 1970; Kirk 1975, 1980). In the arbitrary subdivision of coastal wave energy regimes according to wave height by Dobkins & Folk (1970: 1169), Dimitra beach and Phokas beach clearly fall into the low-energy category. As found by Dobkins & Folk (1970: 1181) and Bartholomä et al. (1998), low-energy gravelly beaches hardly produce diagnostic clast shape parameters, and beach gravels typically retain their shape parameters from fluvial transport.

On Dimitra beach, within-shore sorting of gravel for size, shape, rounding and sphericity support the findings of Lüttig (1964), Bluck (1967) and Bartholomä et al. (1998) that several clast populations of different shape parameters are present on the same beach. Dobkins & Folk (1970), Gale (1990) and Howard (1992), by contrast, stated that beach gravels at least of isotropic material are characterized by distinct shape parameters, at least on high-energy beaches. Dobkins & Folk (1970) and Gale (1990) sampled only the surface of the fairweather beach, and within a narrow strip, with the rationale that „gravels beneath the surface layer which may not have been subject to the influence of active beach processes were avoided" (Gale 1990: 788). The observations on Dimitra beach, however, indicate that the layer involved in active short-term beach dynamics is, at least, 1 m thick and 10-15 m wide, and includes within-shore sorting during the waning stage of high-energy events. In the geological record, thus, the combination of stratigraphic context, sedimentary structures, clast size- and shape-sorting and, if present, fossils and trace fossils best indicates gravelly shore zone deposits (see Fig. 7) (cf. Nemec & Steel 1984; Leithold & Bourgeois 1984; Massari & Parea 1988; Postma & Nemec 1990; Sanders 1997, 1998).

Intervals deposited from progradational gravelly beaches consist of stacked bedsets of conglomerate that are vertically separated by master bedding surfaces that define an oblique-tangential to (depending on the amount of preservation along the beachface/backshore boundary) sigmoidal shape of the bedsets (Fig. 7). At least in the part corresponding to the upper beachface, the master bedding surfaces typically are erosive, and down dip gradually disappear. These surfaces either formed during major storms, and/or because of changes in shoreline configuration, e. g. due to changes in sediment input or lateral shifts in the position of larger beach cusps (Massari & Parea 1988). That beachface conglomerates in microtidal, wave-dominated settings accumulate mainly during the waning stage is supported by locally preserved plunge steps at the boundary between upper and lower beachface, respectively (Fig. 7) (Massari & Parea, 1988).

Although the described gravel ridges are morphologically distinct, because of their ephemeral, mobile nature and their position at the crest of the beach they have a low preservation potential. Presumably, only their lower part may be preserved in the part corresponding to the upper beachface (Fig. 7). The inactive, fairweather part of the storm/swell beachface of Dimitra beach is similar to the „lower beachface", i. e. the „submarine sloping face of the beach" of Massari & Parea (1988: 898). Conglomerates deposited from the "lower beachface" of these authors are characterized by a coarser grain size and by poorly developed, relatively thick and laterally incontinuous bedding, and locally contain steeply dipping bedding surfaces that corresponded to morphologic steps (cf. Massari & Parea 1988, Fig. 14). Similar features of grain size and bedding can be expected if successive storm/swell beachfaces and the swell plunge step such as observed on Dimitra beach become preserved within a progradational succession (Fig. 7).

7 CONCLUSIONS

Along the investigated coastal segment of Kos island, four adjacent sectors are distinguished. (1) Empros beach is a rocky shore with plunging cliffs and a steeply-dipping, submarine talus of boulders. (2) The „coarse-clastic" Thermi beach consists of a subaerial cliff fringed by a beach of coarse gravels to small boulders arranged in seaward-dipping, imbricated fabrics; a plunge step is absent or poorly developed. (3) Dimitra beach is a gravelly beach with a distinct zonation into backshore, cusped beachface, a fairweather plunge step, and a „relic storm/swell beachface" bound seaward by a storm/swell plunge step. (4) The overall finer-grained, gravelly Phokas beach shows a uniformly dipping, even beachface bound seaward by a fairweather plunge step, and an uppermost shoreface of sand and/or gravel. Contemporaneous transgression of these beach sectors left different records. „Rapid" sea-level rise suggested by transgression of the rocky shore were contemporaneous with „gradual" rise recorded by landward shift of gravelly beaches.

Along Dimitra beach, post-storm beach restoration in a swell regime proceeded by size- and shape-sorting of the storm beachface, in feedback with the emergent fairweather beach morphology. On Dimitra beach, the layer involved in dynamic storm/post-storm changes was about 1 meter thick and 10-15 meters wide. In fossil gravelly beach successions, features of high-energy events include berms and erosive master bedding surfaces; features of the waning stage are fairweather plunge steps and relic storm/swell beachfaces (lower beachface). From cuspate gravel ridges of the upper beachface probably only the basal part is preserved.

ACKNOWLEDGEMENTS

The suggestions of an anonymous reviewer and A. Bartholomä are acknowledged.

REFERENCES

Alexandersson, T. (1972): Mediterranean Beachrock Cementation: Marine precipitation of Mg-calcite. - In: Stanley, D. J. (ed.): The Mediterranean Sea. A Natural Sedimentation Laboratory. - 203-223, Stroudsburg (Dowden, Hutchinson & Ross)

Altherr, R., Keller, J. & Kott, K. (1976): Der jungtertiäre Monzonit von Kos und sein Kontakthof. - Bull. Soc. géol. France, (VII), **18**, 403-412, Paris

Bartholomä, A., Ibbeken, H. & Schleyer, R. (1998): Modification of gravel during longshore transport (Bianco Beach, Calabria, southern Italy). - J. Sed. Res., **68**, 138-147, Tulsa

Bernoulli, D., de Graciansky, P. Ch. & Monod, O. (1974): The extension of the Lycian nappes (SW Turkey) into the southeastern Aegean islands. - Eclogae geol. Helv., **67**, 39-90, Basel

Bignot, G. & Guernet, C. (1976): Sur la presénce de *Borelis curdica* (Reichel) dans le Miocène de l'île des Kos (Grèce). - Geol. méditerraine, **3**, 15-26, Paris

Bird, E. C. F. (1969): Coasts. - 246 pp., Cambridge, Massachusetts (The M. I. T. Press)

Bluck, B. J. (1967): Sedimentation of beach gravels: Examples from South Wales. - J. Sed. Petrol., **37**, 128-156, Tulsa

Böger, H., Gersonde, R. & Willmann, R. (1974): Das Neogen im Ostern der Insel Kos (Ägäis, Dodekanes) - Stratigraphie und Tektonik. - N. Jb. Geol. Paläont. Abh., **145**, 129-152, Stuttgart

Bourgeois, J. (1980): A transgressive shelf sequence exhibiting hummocky stratification: the Cape Sebastian Sandstone (Upper Cretaceous), southwestern Oregon. - J. Sed. Petrol., **50**, 681-702, Tulsa

Bourgeois, J. & Leithold, E. L. (1984): Wave-worked conglomerates-depositional processes and criteria for recognition. - In: Koster, E. H. & Steel, R. J. (eds.): Sedimentology of Gravels and Conglomerates. - Canadian Soc. Petrol. Geol. Mem., **10**, 331-343, Calgary

Bundesamt für Seeschiffahrt & Hydrographie (1997): Verzeichnis der Nautischen Karten und Bücher, und sonstigen Veröffentlichungen. - Publikation No. 2452, 112p. Blatt No. 613 „Kuçadasi bis Bodrum", 1:150 000, Hamburg

Dobkins, J. E. & Folk, R. L. (1970): Shape development on Tahiti-Nui. - J. Sed. Petrol., **40**, 1167-1203, Tulsa

Emery, D. & Myers, K. J. (eds.), (1996): Sequence Stratigraphy. - 297 pp., Oxford (Blackwell)

Forbes, D. L. & Taylor, R. B. (1987): Coarse-grained beach sedimentation under paraglacial conditions, Canadian Atlantic coast. - In: Fitzgerald, D. & Rosen, P. (eds.): Glaciated Coasts. - 51-86, New York (Academic Press)

Gale, S. J. (1990): Short Note: The shape of beach gravels. - J. Sed. Petrol., **60**, 787-789, Tulsa

Hart, B. S. & Plint, A. G. (1995): Gravelly shoreface and beachface deposits. - In: Plint, A. G. (ed.): Sedimentary Facies Analysis. - Spec. Publs. int. Ass. Sediment., **22**, 75-99, Oxford (Blackwell)

Howard, J. L. (1992): An evaluation of shape indices as paleoenvironmental indicators using quartzite and metavulcanic clasts in Upper Cretaceous to Paleocene beach, river and submarine fan conglomerates. - Sedimentology, **39**, 471-486, Oxford

Jacboshagen, V. (1986): Geologie von Griechenland. - Beiträge zur regionalen Geologie der Erde, **19**, 1-323, Berlin (Bornträger)

Johnson, M. E. (1988): Why are ancient rocky shores so uncommon? - J. Geol., **96**, 469-480, Chicago

Johnson, M. E., Ledesma-Vasquez, J., Clark, H. C. & Zwiebel, J. A. (1996): Coastal evolution of Late Cretaceous and Pleistocene rocky shores: Pacific rim of northern Baja California, Mexico. - Geol. Soc. Amer. Bull., **108**, 708-721, Boulder

Kirk, R. M. (1975): Aspects of surf and runup processes on mixed sand and gravel beaches. - Geografiska Annaler, Series A, **57**, 117-133, Stockholm

Kirk, R. M. (1980): Mixed sand and gravel beaches: Morphology, processes and sediments. - Progr. phys. Geogr., **4**, 189-210, London (Edward Arnold)

Leithold, E. L. & Bourgeois, J. (1984): Characteristics of coarse-grained sequences deposited in nearshore, wave-dominated environments - examples from the Miocene of south-west Oregon. - Sedimentology, **31**, 749-775, Oxford

Lescinsky, H. L., Ledesma-Vasquez, J. & Johnson, M. E. (1991): Dynamics of Late Cretaceous Rocky Shores (Rosario Formation) from Baja California, Mexico. - Palaois, **6**, 126-141, Tulsa

Longiaru, S., 1987, Visual comparators for estimating the degree of sorting from plane and thin section. - J. Sed. Petrol., **57**, 791-794, Tulsa

Lüttig, G. (1964): Zur Geröllmorphologie von Transgressionskonglomeraten. - In: Van Straaten, L. M. J. U. (ed.): Deltaic and shallow marine deposits. - Developments in Sedimentology, **1**, 253-256, Amsterdam

Maejima, W. (1982): Texture and stratification of gravelly beach sediments, Enju Beach, Kii Peninsula, Japan. - J. Geosci. Osaka City Univ., **25**, 35-51, Osaka

Massari, F. & Parea, G. C. (1988): Progradational gravel beach sequences in a moderate- to high-energy, microtidal marine environment. - Sedimentology, **35**, 881-913, Oxford

Miller, P. R. & Orr, W. N. (1988): Mid-Tertiary transgressive rocky coast sedimentation: Central Western Cascade Range, Oregon. - J. Sed. Petrol., **58**, 959-968, Tulsa

Nemec, W. & Steel, R. J. (1984): Alluvial and costal conglomerates: their significant features and some comments on gravelly mass-flow deposits. - In: Koster, E. H. & Steel, R. J. (eds.): Sedimentology of Gravels and Conglomerates. - Canadian Soc. Petrol. Geol. Mem., **10**, 1-31, Calgary

Pettijohn, F. J., Potter, P. E. & Siever, R. (1987): Sand and Sandstone. - 553 pp., New York (Springer)

Postma, G. & Nemec, W. (1990): Regressive and transgressive sequences in a raised Holocene gravelly beach. southwestern Crete. - Sedimentology, **37**, 907-920, Oxford

Randall, R. E. (1977): Shingle foreshores. - In: Barnes, R. S. K. (ed.): The Coastline. - 49-61, London (John Wiley)

Sanders, D. (1996): The Upper Cretaceous near Maurach (Tyrol, Austria). - Geol. Paläont. Mitt. Innsbruck, **21**, 123-151, Innsbruck

— (1997): Upper Cretaceous transgressive shore zone deposits („Untersberger Marmor" Auct.) in the eastern part of the Tyrol (Austria): An overview. - Geol. Paläont. Mitt. Innsbruck, **22**, 101-121, Innsbruck.

— (1998): Tectonically controlled Late Cretaceous terrestrial to neritic deposition, Gosau Group, Northern Calcareous Alps (Tyrol, Austria). - Facies, **39**, 139-178, Erlangen

Semeniuk, V. & Johnson, D. P. (1985): Modern and Pleistocene rocky shore sequences along carbonate coastlines, Southwestern Australia. - Sed. Geol., **44**, 225-261, Amsterdam

Wachendorf, H. & Gralla, P. (1983): Korrelation der präneogenen Serien im NE-Dodekanes (Griechenland) - Z. dt. geol. Ges., **134**, 95-117, Hannover

Willmann, R. (1983): Neogen und jungtertiäre Entwicklung der Insel Kos (Ägäis, Griechenland). - Geol. Rdsch., **72**, 815-860, Stuttgart

Manuscript received September 20, 1998
Revised manuscript received March 8, 2000