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Origin of sediment ripple bands and zones on the inner shelf of southern Monterey Bay, California

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**Origin of sediment ripple bands and zones on the inner shelf of
southern Monterey Bay, California**

Mariant, Judy J., M.S.

San Jose State University, 1993

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ORIGIN OF SEDIMENT RIPPLE BANDS AND ZONES
ON THE INNER SHELF OF SOUTHERN MONTEREY BAY, CALIFORNIA

A Thesis

Presented to San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Geology

By

Judy J. Mariant

December, 1993

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ABSTRACT

The Southern Monterey Bay is an entire littoral cell characterized by a series of rip-currents, a weak southward-flowing longshore current caused by wave action, and a weak offshore current near Monterey. Shore-normal zones and shore-parallel bands of rippled coarse-grained sediments are found throughout Monterey Bay. These features are 1-1.5 km offshore in water depths of 10-30 m with wavelengths of 0.5-3.0 m and wave heights of 0.16-1.50 m.

A series of side-scan mosaics constructed with multiple track lines reveal seasonal variations in the geometry of the rippled bands and zones. The tendency for ripple spacing to increase with decreasing depth indicates that large symmetrical ripples are oscillatory wave ripples, with spacing proportional to the diameter of orbital wave motion (Clifton and Dingler, 1984).

Offshore currents aligned along the shore-normal zones were inferred from deviations in velocity and course changes in the R.V. Ricketts. Aerial photos show that shore-normal zones of ripples coincide with sites of rip currents that transport the sediment offshore during times of heavy surf activity.

The bands are lag deposits that are located in scoured depressions, presumably formed during storms, and represent temporary offshore depocenters of coarse-grained sediment.

INTRODUCTION

Shore-normal zones and shore-parallel bands of rippled beds of coarse-grained sand are located throughout Monterey Bay (Fig. 1 & 2). These features are 1.0-1.5 km offshore in water depths of 10-60 m. Ripple wave lengths vary from 0.5 to 3.0 m and the wave heights are approximately 0.2 to 2.0 m. The source of the sand in these bands and zones is beach, back beach and dune erosion.

In 1983 up to 2.59 m of erosion occurred during one significant storm season (Griggs & Jones, 1985, Table 1). As sea level continues to rise, erosion, offshore transport and offshore deposition rates will continue to be high and could increase. Several environmental factors contribute to the observed coastal erosion, including offshore sediment transport, regional tectonics, distribution of geologic formations, nearshore circulation patterns, and the intensity and direction of wave patterns.

The purposes of this study are: 1) to determine if there is a seasonal or storm-induced migration of these bedforms, 2) to apply wave theory to wave and current data collected in Monterey Bay in order to explain the rippled features by comparing models that relate bedforms to ripple geometry, wave conditions, and grain size, and 3) to examine rip currents, storm induced downwelling and currents generated by wind and wave action as a potential mechanism of offshore sediment transport.

Figure 1. Location of navigation lines, rippled zones and bands of coarse sand shown on side-scan sonar taken in 1989 and 1990. Sonograms of feature A, B and C are shown on figure 2.

Figure 2. Sonographs of rippled coarse grained features shown on figure 1. A. is a sonograph of a patchy rippled band. B. is a sonograph of a large rippled band. C. is a sonograph of a rippled shore-normal zone. Locations of A, B, and C are shown on figure 1.

Table 1. Shoreline Erosion Rates for Southern Monterey Bay

Location	time span	m/yr	reference cited
Marina	1937-1983	1.7-1.8	Jones (1983)
Marina	1937-1986	1.1-1.5	Johnson et al. (1987)
Marina	1915-1986	0.8-3.0	Griggs & Savoy (1985)
Fort Ord	1956-1983	3.6-4.6	Arnal et al. (1973)
Fort Ord	1920-1973	0.4-1.5	Arnal et al. (1973)
Fort Ord	1950's	0.9	Arnal et al. (1973)
Fort Ord	1960's	1.5	Arnal et al. (1973)
Fort Ord		1.8-2.6	Smith (1983)
Fort Ord	1920-1985	1.9-2.6	Griggs & Savoy (1985)
Sand City	1932-1983	1.2-1.9	Jones (1983)
Sand City	1932-1970	0.4-0.8	Welday (1972)
Sand City	1946-1967	1.2-3.0	Griggs & Savoy (1985)
Monterey	1939-1978	0.3-0.5	Thompson (1981)
Monterey	1958-1983	0.3-0.5	Jones (1983)
Del Monte Beach	1956-1984	0.4	Griggs & Savoy (1985)

Table 1. Shoreline erosion rates for southern Monterey Bay. Erosion rates represent the landward migration of the shoreline, are shown in meters per year and have been collected from the references cited on the table.

Geologic Setting

Monterey Bay is the largest open embayment (Fig. 1) on the California coast and it is characterized by a wide shelf split by the Monterey Canyon. The bay is 40 km long in a north-south direction and extends to the edge of the continental shelf, which is less than 20 km west of the bay's eastern shore. Southern Monterey Bay extends from the head of the Monterey submarine canyon at Moss Landing southward to the Monterey Peninsula. The southern shelf slopes gently ($1-2.0^\circ$) seaward, with bathymetric contours that are approximately parallel to the shoreline. Isobaths from depths of 70 meters and inland reflect the U-shaped shoreline of the southern end of the bay.

The Monterey Bay area is divided into smaller blocks and basins that are separated by southeast-northwest trending faults. Basin development within the Salinan block began sometime in the Neogene and is continuing to the present (Greene, 1977). Uplift and subsidence of crustal blocks in this region is believed to result from wrench fault tectonics. The Salinas Block (Fig. 3) is affected by a broad tectonic downwarp. Based upon sediment thickness, Dupre (1975) and Tinsley (1975) suggest that the southern Monterey Bay has been continuously subsiding throughout the Quaternary. Rising eustatic sea-level and tectonic subsidence combine to cause a

Figure 3. Map showing the divisions of the Salinian Block into the various blocks and basins that are separated by southeast-northeast trending faults. (from Greene et al., 1977)

regional sea-level rise in the area.

The downwarped Salinas Block forms a topographic basin. During the last glacial low stand of sea level that peaked at 18 kya (Dupre and Clifton 1979), an abundant supply of sand in the area initially formed broad flat beaches. Dry sand on the back beach was blown inland by the prevailing northwesterly winds, initially forming a backshore berm or foredune. The high sand supply in the region produced a series of dunes during the Wisconsinian and pre-Wisconsinian called the Monterey dune complex (Cooper, 1967) that extends from Moss Landing to the Monterey Harbor. The dune complex consists of three geological units: 1) recent dunes that fringe the shoreline near the Salinas River, 2) Wisconsin dunes that form a narrow belt along the coast from the Salinas River to Monterey, and 3) pre-Wisconsin dunes extending from the Salinas River to Monterey and inland up to 7 miles (Fig. 4). The recent dune belt formed as older dunes were eroded and reworked in response to eustatic sea-level rise beginning after the last glacial low stand 18 kya (Cooper, 1967).

From Monterey harbor to the tip of Monterey Peninsula the shoreline consists of outcrops of granodiorite. The granodiorite is highly resistant to erosion and forms the rocky promontories of the Monterey Peninsula. Interspersed between these rocky promontories are a series of small sandy pocket beaches. The beaches from the Salinas River to

Figure 4. Monterey Bay Dune Complex showing the Recent, Wisconsin, and Pre-Wisconsin dunes and the prevailing wind direction. (after Cooper 1967)

Monterey are narrow, and subject to high-energy wave impact (Chin, et al., 1988). The coarse-grained material (Fig. 5) of these beaches has been derived from ancient beach and offshore deposits uncovered by erosion of the overlying dune deposits. Site inspections and aerial photographic studies of the beaches have identified a rhythmic topography consisting of a series of beach cusps and troughs which run offshore at an oblique angle (Fig. 6).

Currents and Circulation

Circulation in Monterey Bay is strongly influenced by the circulation patterns farther off the coast. The available information on the central California Coast indicates a complex circulation system. Breaker and Broenkow (1989) surmised that the combination of the offshore currents and submarine topography sets up the general circulation patterns of water in the southern portion of the bay. Coastal upwelling often starts abruptly in the spring north and south of Monterey Bay; upwelled water from those areas may be advected into the Bay. Offshore upwelling occasionally occurs across the entrance of Monterey Bay between March and October. Onshore flow in the Monterey Canyon is consistent with bathymetrically induced upwelling, where cold saline water follows the slopes of the canyon up to the head and then spreads out over the shelf areas. Seasonal changes in the deep circulation may be related to variations in the strength

Figure 5. Grain size on the beach and in the near shore zone on Fort Ord near Stillwell Hall. The numbers on the beach profile refer to the site locations on the graph above. (Beach profile after Komar, 1976)

Figure 6. Aerial photograph of study area arrows point to a rip cell and plume of sediment entrained in a rip current.

of the California Undercurrent.

Waves and Tides

Swell is the most significant source of wave energy in Monterey Bay (Smith, 1993) and is characterized by both Pacific Ocean swell (wave periods of 8 sec and greater) and locally generated wind waves. Early spring and summer are characterized by swell from the southwest, while in the fall and winter, swell is from the west and northwest (Fig. 7). The rocky headlands at Point Pinos and Point Santa Cruz and combined with the Monterey Submarine Canyon, act to bend the wave-front into a shape similar to that of the shoreline (Sklavidis et al., 1985)

The distribution of sediments in Monterey Bay and the shoreline shape are, in a large part, a response to wave conditions. Sediments found near the shore, where waves affect the bottom, tend to be coarser than those found offshore (Smith, 1983). Storms from the west to northwest, during the winter have the greatest impact resulting in high waves along the Fort Ord coastline in Monterey Bay (Smith, 1983; Thornton, 1985).

Tides in Monterey Bay exhibit the diurnal inequality typical of most of the west coast of North America. The Monterey Canyon moderates both tidal ranges and tidal influence on coastal currents. Data from the National Oceanic Atmospheric Administration (NOAA) indicate that the tidal

Figure 7. Seasonal directions of wave approach and wave refraction patterns in Monterey Bay. Fall and winter swell is from the west and norththwest (A & B) While Early spring and summer swell is from the southwest (C) (After Weigle, 1965)

current is too weak and variable to be predicted, and seldom exceeds 0.1 knot (25 cm/sec). The tidal parameters for the southern Monterey Bay are a mean range of 1.07 m, diurnal range 1.62 m, and mean tidal level 0.85 m mllw (NOAA, 1983).

Near Shore Circulation

Near shore circulation of ocean water responds to wave activity that occurs during the three seasonal directions of wave approach (Fig. 7). Longshore currents result from waves striking the shore at an angle to the near shore bottom configuration. Welday (1972) found that during the late fall, winter and early spring the prevailing wave crests in southern Monterey Bay are N 10° E to N 20° E, with their orthogonals averaging about N 75° W (WNW). With waves from this direction, southward littoral migration occurs from the mouth of the Salinas River to Sand City. From that point southward to Seaside the wave fronts are parallel to the shoreline, and therefore significant littoral transport is not likely. From Point Pinos to Seaside littoral drift dominates and ultimately turns offshore.

Dorman (1968) found a series of rip current cells and a southward flowing longshore current caused by wave action along the eastern bay shore (Fig. 8). This current does not continue along the coast, but turns seaward just south of Sand City where it is met by a weak cyclonic gyre that predominates

Figure 8. Rip currents and longshore sediment transport patterns in southern Monterey Bay. (After Dorman, 1968)

in the southern bay (Dorman, 1968).

Several studies have suggested that the southern portion of Monterey Bay comprises a nearly complete littoral cell with boundaries at the Monterey Canyon and at Point Pinos (Fig. 9) (Dorman (1968), Dittmer (1972), and Oradiwe (1986). Major sediment inputs include the Salinas River, erosion of dunes bordering the beaches, shoreline erosion and abrasion of the granodiorite exposed on the Monterey Peninsula. The entire cell is thought to be stable in shape and size, in spite of the high erosion rates (Table 1) in the area (Griggs and Jones, 1985).

Near Shore Sedimentary Processes

Inman (1957, 1963) investigated oscillatory ripples from the surf zone to a depth 50 meters along the sandy shelf bordering the coasts of southern California, Mexico, and the Hawaiian Islands. With supplementary information from laboratory measurements he found a relationship between ripple spacing and orbital diameter. As orbital diameter increases, ripple spacing increases until a maximum is reached and the ripples fade out and sediment transport is initiated (Fig. 10). Komar (1976) found that rip current cell circulation can redistribute beach sediments and have a profound effect on beach configuration and sediment transport. For example, troughs scoured by rip currents may act to stabilize the rip current position. The cell circulation is then strongly

Figure 9. Littoral cell boundaries and sediment sources and losses in southern Monterey Bay. (From Dorman, 1968)

Figure 10.

Bedforms and structures formed by water waves. A. Relationship between sand motions in a rippled sea bed and the orbital motions of waves with and without a unidirectional current. (After Komar, 1976) B. Diagnostic internal features of wave-formed ripples (after de Raaf et al. 1977). C. Threshold orbital velocity required for motion of quartz grains, and D. the water depth and wave height required. (From Komar and Miller, 1975)

affected by the beach topography and is not completely free to respond to changing conditions of swell waves and edge waves. The seaward flow of a rip current occurs where the waves and the set-up is lowest and the longshore currents converge (Fig. 11). The cell circulation therefore depends on the existence of variations in the wave height along the shore.

In a wave basin, swell waves may generate standing edge waves on the beach that have the same period as incoming waves. Edge waves are standing waves with crests normal to the shoreline. Edge waves are best observed as a series of tongues of swash that run up on the beach face and the wave height is greatest at the shore and decreases rapidly offshore and fading out past the breakers. The interaction of the incoming swell and edge wave produces high and low sections of the incoming breakers and forms a regular pattern of circulation cells with evenly spaced rip currents (Fig. 11). A significant factor can be the interactions between the edge wave and the incoming swell is the generation of cell circulation. The large and small breakers remain at fixed antinode positions, every other antinode is the site small breakers. Since the rip currents occur at every other antinode which is a site of small breakers, a regular pattern of rip currents and cell circulation is produced.

Niedoroda et al. (1984) have shown that during non-storm conditions there is a tendency for sand to be moved only on

Figure 11.

Rip cell morphology. A. Addition of the incoming swell and the standing edge wave at the breaker position give a longshore variation in the observed breaker height. The net height is greatest where the incoming wave are in phase and lowest where they are 180° out of phase. B. The positioning of the rip currents is where the breaker height is smallest that is where the edge waves and the incoming wave are 180° out of phase. (from Komar, 1976)

the upper shoreface by asymmetrical near bottom wave orbital velocities. During storms the larger waves increase near-bottom orbital velocities that entrain sand over the entire shoreface. Sand is then transported both parallel and normal to the shore. Transport extends across the shoreface onto the inner continental shelf. In an erosional regime where sea level is rising sufficiently with respect to the rate of sediment input, Niedoroda et al. (1984) suggest that storm induced downwelling currents move sand seaward faster than wave orbital currents can return it. The primary sediment source is the shoreface and storms can strip away the entire beach prism and back-barrier. Presumably the inner continental shelf an important sink for the material eroded from the shoreface.

Rippled zones parallel to the shore and shore-normal bands of coarse sand have been observed on sonographs of the inner continental shelf of southern Monterey Bay (Hunter et al., 1988), between Bodega Bay and Point Arena (Cacchione et al., 1984) and along the moderate to high energy Pacific coast of Mexico (Reimnitz et al., 1976). Hunter et al. (1988) studied rippled zones and bands of coarse sediment at water depths between 10-30 meters that are approximately 20-100 meters wide, and 1 km from shore. These workers observed changes in the length, width and locations of the coarse sediment bands and zones by comparing series of side-scan

sonar surveys. They proposed three modes of offshore transport: 1) seaward-flowing rip currents, 2) seaward flowing bottom currents that are generated in part by storm winds, and 3) other currents including Langmuir currents that are generated in part by wave and wind action.

Cacchione et al. (1984) described rippled scour depressions on the inner continental shelf off Central California that are similar to those observed in southern Monterey Bay. They found elongate depressions normal or slightly oblique to the general trend of the isobaths and containing large, long crested ripples, and smooth areas of no perceptible relief on side scan records, but covered with well defined oscillatory ripples (wavelengths of 20-30 cm; heights of 2-5 cm) distributed along the coastline between Bodega Bay and Point Arena. Current and wave data taken seaward of Bodega Bay and Point Arena during storms suggest that nonuniform downwelling-induced currents and large waves are the cause of these features. Southern winds that could produce downwelling are common along the central California Coast during late fall and winter storms. They concluded that the ripples are wave-formed based upon existing models relating ripple geometry to wave conditions.

Side-scan sonar records of Reimnitz et al. (1976) taken along the high-energy Pacific coast of Mexico show ripple-marked bands normal to the surfline. These bands were traced

as far seaward as 1.5 km to depths of 30 m. The ripple marked bands were observed only near the coast and not on survey tracks seaward of the 30 m contour. Areas with ripple zonation generally correspond to areas where pronounced rip-current heads were crossed or seen a short distance shoreward. Reimnitz et al. (1976) suggested that this correspondence is indicative of ripple bands produced by rip currents. They also suggest that rip currents that develop under severe wave conditions transport sediment, modify the seafloor, and produce internal sedimentary structures much farther seaward than was previously believed.

METHODS

This study was designed to determine the origin of the sediment ripple bands and zones in the southern Monterey Bay. Sediment transport processes were evaluated and the role of seasonal or storm induced migration of these rippled beds was investigated. Side-scan sonar, cores and aerial photo studies documented changes in the nearshore morphology, changes in the location and scale of rip currents, changes in the size, shape and location of the rippled beds, as well as sediment grain size and lithology that compose the ripples.

Side-Scan Sonar

Side-scan sonographs were collected along ship's tracks on December 16, 1991, February 24, 1992, April 27, 1992 and

June 22, 1992 aboard the R/V Ricketts (Fig. 12, Appendix I). Navigation was provided by a North Star 800 Loran-C system. The navigational system is pre-set to an established latitude and longitude bias from the U.S. Navy G.P.S. receiver. This system gives a repeatable accuracy variation of 4.5-5.0 m. Even with this equipment it was difficult to stay on course due to wind, waves, visibility and equipment failure. Depth was recorded on a 200 Khz Lowrance model X16. Side-scan sonographs were collected on a Klein Digital Sonar System 590. The system produces a "plan view" photo-like image of sea floor acoustic scattering. Transducers mounted on both sides of the 1.02 m long towfish emit a 100 KHz frequency acoustic signal. Differing intensities of the acoustic scatter signal produce images of the sea floor similar to those produced by aerial photography, although the source of backscatter is complicated. The backsides of positive topographic features are marked by an acoustic shadow or light regions on the records that are caused by blockage of the acoustic scatter. Outcrops of bedrock and sand ripples produce dark images, as a result of high acoustic backscatter, whereas depressions, fine-grained sands, and muds produce lighter images, indicative of less backscatter. A swath width of 200 meters (100 meters per side) was used and survey lines were laid out to provide a minimum of 20 meters (10%) of overlap between lines. Records from all cruises were used to construct three

maps to show changes in the configuration of the sand waves.

Cores

Gravity coring was tried but due to the sandy nature of the substrate proved to be ineffective. The corer bounced off the coarse grained rippled beds and landed on its side.

Diver-operated push-down box corers and a pound-down corer on loan from the U.S. Geological Survey, were used on June 22, 1992. Cores were taken from the center and adjacent to the rippled bedforms. Cores from the pound-down corer were used to determine surface stratigraphy of the beds, while samples from the box cores were used for grain size analysis. The divers also measured the ripple height and wavelength for comparison to measurements from the sonographs. Two 0.5 m cores and one 0.30 m box core was taken in the rippled site and one 0.5 m core and one 0.30 m box core was taken adjacent to the site.

Aerial Photographs

Aerial photographs of the southern Monterey Bay shoreline were studied at the University of California at Santa Cruz map library. This study was done to determine: 1) if the rhythmic topography, consisting of longshore bars separated by rip currents migrates in the longshore direction seasonally, 2) do the rippled zones found offshore migrate as well, and 3) does the spacing of longshore bars remain constant and is it similar to the spacing of the shore-normal zones.

Wind and Wave Data

Wind and wave data used in this study were gathered from the Coastal Data Informational Program Monthly Reports, a cooperative program of the U.S. Army Corps of Engineers and California Department of Boating and Waterways. Data were recorded at measuring stations in the Marina array. This information was used to determine if waves can produce the threshold velocity needed to transport sediment in the study area.

DATA PRESENTATION

Maps

The location maps of the rippled bands and zones (Fig. 12), prepared from the images on the side-scan sonographs, revealed temporal changes in the geometry of these features. On the sonographs the rippled bands and zones are darker than the surrounding fine sand, have a visibly rippled pattern and are sharply bounded. Depth records and shadow effects on the sonographs indicate the depressions are smooth except for the ripples and are up to 1 m lower than the surrounding area with steep sides. A chart (Fig. 13) was prepared to examine the variations of ripple spacing with time and distance from shoreline.

Cruise I

Sand waves are clearly delineated (Fig. 14) on the sonar records taken on December 16, 1991. Large shore-normal zones

Figure 12. Maps showing the December through June changes in the shape and size of the bands and zones of rippled coarse grained sediments in southern Monterey Bay.

Ripple Wavelengths Off Fort Ord
December 16, 1991, February 24, 1992, April, 27, 1992

Figure 13. A. Ripple wavelength diagram showing the difference in the spacing on different navigation lines. Line 1 is closest to the shore and line 4 is the farthest off shore. B. Schematic diagram of the wave orbital velocity, the orbital diameter near the bottom, and the generated oscillatory ripple marks (After Clifton and Dingler 1984).

Figure 14. Mosaic of sonograms taken on Cruise I, December 16, 1991. The location, orientation and navigation line is shown on Fig. 12.

of sand waves were located in the northern and central portions of the study area (Fig. 12). The significant wave height was 1.2 m with a period range of 12-16 seconds (Appendix II). The significant wave height for the previous seven days ranged from 1.1 to 2.3 m with an average of 1.7 m; periods ranged between 10-16 seconds. The seas were calm and there was no wind, this facilitated the detection of currents normal to the shoreline at various locations (Fig. 12). At these sites the velocity of the R/V Ricketts changed from 2.9-3.2 knots to 2.6-2.8 knots and it was necessary to alter the course by 10° to 15° to correct for sideways drift. Using the law of cosines, surface current speeds were estimated between 1-2 knots (0.70-1.00 m/sec, 70-100 cm/sec.) based on the deflection of the ship's course. These currents appear to exceed the threshold velocity needed to initiate sediment motion at depths up to 30 m (Fig. 15) for grain sizes up to 10 mm.

Cruise II

The sonar records taken on February 2, 1992 are not as clear (Fig. 16) which is probably due the high sea state. The towfish may have suffered from yaw and pitch, thus degrading the sonograph. The most dominant features were, however, mapped (Fig. 12). The shoreward portions of the sonographs along navigation line 1 exhibit diffuse high backscatter areas

Figure 15. Stability fields of bedforms in sand and silt. Graph shows the flow velocity for a unidirectional current with respect to grain size. (from Harms et al., 1975)

Figure 16. Mosaic of sonograms taken on Cruise II, February 2, 1992. White arrows point to a possible cloud of suspended sediment. The location, orientation and navigation line is shown on Fig. 12.

that has been inferred as clouds of suspended sediment by Hunter et al. (1988). On navigation line 4 (Fig. 12) high acoustic backscatter that may be rocks were noted 1 km offshore from Stillwell Hall. The maximum daily significant wave height was 3.0 m with a period range of 10-12 seconds (Appendix II). It was difficult to stay on course due to swell height and the R/V Ricketts was pushed offshore at various sites (Fig. 12) by apparent off-shore currents. Velocity changes due to shore normal currents changed the boat speed from 3.1-3.3 knots to 2.6-3.1 knots. Using the law of cosines or vector addition, surface current speeds of 1.0-2.0 knots (0.70-1.0 m/sec, 70-100 cm/sec) were calculated for the offshore surface currents.

Cruise III

The sonar records taken on April 27, 1992 show rippled beds (Type A) grading into a second set of possibly older, pre-existing rippled beds (Type B), with gradational boundaries (Fig. 17). Only the clearest or dominant features were mapped. The significant wave height that day was 1.1 m with a period of 10-12 seconds, winds from the NW were strong and it was difficult to stay on course. There may have been offshore currents; however, due to the wind it was not possible to tell if the boat was pushed off course by wind or by a current.

Figure 17. Mosaic of sonograms taken on Cruise III, April 27, 1992. Brackets show the location and interface of two distinct types or ripples. Type A is the dominant feature mapped on Fig. 12. The location, orientation and navigation line is shown on Fig. 12.

Figure 18. Mosaic of sonograms of longitudinal ridges taken on Cruise I, December 16, 1991. Sand or gravel waves with a wavelength of about 21 meters. The crests are mostly sinuous or herringbone pattern and extend at approximately right angles to the trend of the incoming train of waves. The abrupt boundary around the rippled band is caused by a shadow effect indicating that the ripples are in a scour depression that is 1 m lower than the surrounding area. The location, orientation and navigation line is shown on Fig. 12.

Longitudinal Ridges

Records from all three cruises display a series of ridges and troughs (Fig. 18) that are perpendicular to the shoreline. This longitudinal relief pattern becomes more widely spaced and less defined with increasing water depth. The wavelengths and heights of these features also varied on each cruise (Fig. 19), possibly as a result of changes in the wave regime (Komar, 1976). The ridges mapped on Cruise I exhibited a maximum wavelength of 20 m, whereas during Cruise II wavelength maximum was approximately 25 m and 15 m during cruise III.

Cores

Cores 1 and 2 (Fig. 20), which were collected from the shore parallel bands, penetrated through 0.25 m of coarse sand before entering bioturbated fine sand. The coarse grained fraction includes pebbles and shells. Most of the pebbles are of granitic composition similar to the granodiorite on Monterey Peninsula and all of the shells are lying with the concave side downward. Stratification varies from well-defined to nearly absent and bedding planes are flat to moderately inclined up to 20°. The median angle of cross-bedding dips in two opposing directions, creating a chevron pattern similar to those shown in figure 10 B, indicating an oscillatory flow (Komar, 1976; de Raaf et al., 1977; and

Longitudinal Ridge Wavelengths Off Fort Ord

Graphs of the wavelengths of the longitudinal ridges for the cruises on December 12, 1991, February 2, 1992 and April 17, 1992. Data points are an average from each cruise.

Figure 19.

GRAIN SIZE Off shore, Fort Ord

A.

B.

Figure 20.

Core stratigraphy and grain size graph. A. shows the results of grain size analysis on the sediment in the cores. B. shows the stratigraphy and lithology of the cores.

Clifton and Dingler, 1984) (Fig 10). The fine grained material below is highly bioturbated and is grayish brown grading down to mottled black to olive brown.

Core 3 collected adjacent to the rippled beds penetrated through the fine sand up to 0.50 m and did not contain coarse sand beds as found in cores 1 and 2. This core consisted entirely of highly bioturbated fine-grained sand and silt that graded downwards from a sandy grayish brown to mottled black sand and olive brown sand.

Aerial Photographs

Aerial photographs studied at the University of California at Santa Cruz Map Library show that the beach cusps, bars and trough spacing change in size, and at times, are absent. All of the aerial photographs indicate that the angle and direction of wave approach is such that the longshore current is from north to south.

Photographs taken on April 2, 1986 reveal predominant cusp and trough features that are largest near Marina and Fort Ord, and decrease in size southward. Rip cell spacing ranged from 360-900 m and visible plumes of suspended sediment extended 420 to 920 m offshore (see Fig. 6 for an example). The spacing and visible plumes of suspended sediment are largest near Stillwell Hall on Fort Ord. Although these photos are 5-6 years apart the locations of the troughs and rip-current generated plumes of suspended sediments are very

close to the locations of the shore normal zones of rippled coarse sand located on the sonar mosaics taken on December 16, 1992 (Fig. 12). The angle of wave crests with the shoreline is 20° decreasing to 0° to the south. Aerial photographs taken April 12, 1984 show similar patterns of well defined cusp and trough morphology that is best developed near Marina and Fort Ord, but then decreases in size southward. The cell spacing ranges from 240-780 m and plumes of suspended sediment extend 480-720 m offshore.

Photos taken May 6, 1978 and February 12, 1984 show the largest spacing and plumes near Stillwell Hall and decreasing in size until they disappear in the south. The spacing of the rip cells ranged from 120-420 m and plumes of suspended sediment extended 180-360 m offshore. The angle of the wave crests with the shoreline is 10° - 15° decreasing to 0° to the south.

Photos taken October 5, 1976 and June 24, 1980 show no cusps, troughs, or plumes of suspended sediment extending offshore. The angle of the wave crests with the shore line is 10° - 15° decreasing to 0° to the south.

DISCUSSION

Erosion along the shore of Monterey Bay occurs when powerful winter storm waves, coupled with high tides, are able to rush up the foreshore and scour away at the base of

unconsolidated sand dunes (Mc Gee, 1986). The dune is undermined, causing its face to collapse and fall onto the berm. Successive waves entrain the sediment and carry it into the littoral transport zone.

The sizable erosion rates in the Southern Monterey Bay are due to the impact of high energy waves (Griggs and Jones, 1985). Although the orthogonals diverge (Fig. 7) swell from the NW loses little energy from interaction on the bottom as it passes over Monterey Canyon.

This high energy wave impact has set up a series of large scale rip currents spaced up to 900 m apart and plumes of suspended sediment extending up to 920 m offshore. Cowell (1986) observed large-scale rip currents or "mega rips" on the inner continental shelf of Australia and suggests that this process is responsible for the seaward transfer of water and sediment across the shoreface and on to the inner continental shelf. The inner shelf floor becomes a major depocenter for sediments eroded from the shoreface. While the eroding shoreline is the primary source of sediment, a single storm can remove the entire beach, back shore berm and erode the dune face.

Rip currents and wind generated downwelling (Niedoroda et al., 1984), which become most active during storms, transport sediment from the littoral zone seaward. Water velocity, seaward distance, and spacing of these rip currents are

directly proportional to wave energy and become well developed during high-wave events. Sites of large scale rip currents appear to be stationary for the season. Consequently the shore normal zones (Figs. 14, 16, 17) may provide important sites of offshore transport by the large scale rip currents.

At times of storm activity, wave action scours the bay floor sufficiently to form depressions as described by Clifton et al. (1971). During these storms the intensified currents winnow the sediment and produce laterally extensive lag deposits consisting of shell fragments, pebbles and coarse sand in the depressions. The range in length, width and depth of these lag deposits is difficult to establish. They appear as large scale bed features in scoured depressions. They are from 1,000 to 1,500 m offshore, in an area 30 to 120 m wide. Most are beneath the outer portion of the zone of wave buildup, which is at a depth of approximately one-half of the deep water wavelength and the wave begins to interact with the bottom. The dominant bedform is a distinctive ripple that shows considerable variation in size and spacing (Fig. 14, 16, 17).

The large symmetrical ripples in the coarse sand zones and bands are wave ripples. The tendency for the ripple spacings to increase with decreasing depth (Fig. 13) suggests that the ripples are of the orbital type as described by Clifton and Dingler (1984), with spacing proportional to the

orbital diameter of wave motion (Inman, 1957, 1963). The period and height of the waves that form the ripples were calculated using the method outlined by Clifton and Dingler (1984), which is based upon Komar (1976). Using a ripple spacing of 0.8 m, sediment grain size of 0.5 mm, and water depth of 20 m, the calculated wave period is 11.6 sec and wave height is 1.4 m. Wave periods of 10-12 sec and wave heights of 2 m are common in the study area, suggesting that the ripples are not produced by storm conditions and that they are oscillatory wave ripples formed between storms.

The longitudinal ridges and troughs found on the sonograms (Fig. 18) are oriented parallel to the direction of rip currents. They appear as a series of ridges and troughs that produce a herringbone like pattern intermeshed with and bending the ripples in the bands and zones. These features may be a part of a rip cell circulation or edge waves. Komar (1976) states that if the incoming waves and edge waves have the same period, the large or small breakers remain at fixed antinode positions, with every other antinode position being the site of large breakers and the alternate antinode the position of small breakers. This theory could explain the location of the longitudinal ridges at the site of large breakers and the troughs at sites of small breakers.

Another possibility is that the longitudinal ridges form where longshore currents have the least interference with

incoming waves, at the antinodal points. The longitudinal ridges may be sand waves formed by the longshore current. This could also lead to the conclusion that antinodes and standing edge waves may be partially driven by longshore currents.

The near shore cell circulation consisting of rip currents and longshore currents is normally generated by variations in the wave height along the beach (Komar, 1976; Bowen, 1969; Bowen and Inman, 1969). The water level shoreward of the higher breakers is raised above that of smaller waves, resulting in a net flow toward the position of small waves, where it converges and turns seaward as a rip current. This process is enhanced by wave refraction causing divergence and convergence of the wave rays or by edge waves interacting with the normal swell.

CONCLUSIONS

The shore-normal zones and shore-parallel bands of rippled coarse-grained sediment in Monterey Bay hold key evidence of ongoing shoreline erosion in the area. Erosion results from a eustatic sea level rise after the last glacial low stand 18 kya (Dupre and Clifton, 1979), coupled with subsidence and tilting of the offshore Salinas Block.

As sea level slowly rises the coastal dunes that fringe the southern Monterey Bay and the underlying beach and near shore deposits are eroded. This eroded material is reworked

and the finest-grained material is transported offshore; the medium to fine-grained component is blown inland and the coarsest material remains on the beach (Cooper 1967). During periods of high waves coarse grained sand on the beach is transported across the shoreface to the inner continental shelf in channels formed by large scale rip currents. Simultaneously the storm surf scours the bay floor, thereby producing depressions parallel to the shoreline and forming lag deposits consisting of pebbles, shell fragments and coarse sand similar to those described in Clifton et al. (1971). At this time the fine grained material is entrained as suspended sediment and is removed from the site. The ripples on the lag deposits and in the rip channels are formed between storm events. The large symmetrical shore parallel ripples found in bands and zones are oscillatory wave ripples with a tendency for ripple spacing to increase with decreasing depth (Clifton and Dingler, 1984).

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Appendices

The following appendices contain the navigational data recorded on all of the cruises and wave data for the seven months of this study.

APPENDIX I

Navigation lines plotted with rippled bands and zones of coarse grained sediment.

APPENDIX I
NAVIGATION LOGS
DECEMBER 12, 1991

line 1				line 2			
lat	long	Boat Speed knots	comments	lat	long	Boat Speed knots	comments
36 38.30	121 50.47	2.9	fish in	36 40.70	121 49.46	3.2	begin line 2
36 38.48	121 50.43	2.9	begin line 1	36 40.47	121 49.61	3.2	
36 38.77	121 50.34	2.9		36 40.13	121 49.72	3	
36 38.92	121 50.25	2.9		36 39.88	121 49.81	3.3	
36 38.99	121 50.21	2.9		36 39.64	121 49.95	2.8	
36 39.24	121 50.10	3.2		36 39.40	121 49.05	3.2	
36 39.46	121 50.00	2.9		36 39.16	121 50.18	2.9	
36 39.70	121 49.88	2.7	current noted	36 38.95	121 50.30	3.1	
36 39.93	121 49.79	2.8		36 38.70	121 50.41	3	
36 40.17	121 49.67	3.1		36 38.46	121 50.52	3	
36 40.40	121 49.56	2.8		36 38.23	121 50.62	3	
36 40.63	121 49.42	3		36 38.08	121 50.69	3	end of line 2
36 40.71	121 49.37	3	end of line				
line 3				line 4			
lat	long	Boat Speed knots	comments	lat	long	Boat Speed knots	comments
36 37.87	121 50.91	2.9	begin line 3	36 40.71	121 49.81	3	
36 38.26	121 50.82	3		36 40.43	121 49.92	3.1	
36 38.40	121 50.71	2.9		36 40.19	121 50.04	3.1	
36 38.65	121 50.62	3.1		36 40.94	121 50.15	3.1	
36 38.90	121 50.51	3.1		36 39.69	121 50.24	3	
36 39.11	121 50.44	2.7	current noted	36 39.44	121 50.35	3	
36 39.35	121 50.34	2.9		36 39.20	121 50.46	3.2	
36 38.58	121 50.24	2.9	change	36 38.97	121 50.55	2.9	
36 39.76	121 50.17	3		36 38.74	121 50.65	2.7	
36 39.99	121 50.06	3.2		36 38.53	121 50.73	2.6	
36 40.26	121 49.93	3		36 38.31	121 50.84	2.8	
36 40.44	121 49.83	3		36 38.07	121 50.92	2.6	
36 40.67	121 49.66	3.8	end of line 3	36 37.91	121 51.01	2.8	end of line 4
line 5							
lat	long	Boat Speed knots	comments				
36 37.87	121 51.11	2.6	begin line 5				
36 38.12	121 51.00	2.7					
36 38.39	121 50.89	3.1					
36 38.60	121 50.81	3.1					
36 38.83	121 50.72	3.2					
36 39.06	121 50.62	2.9					
36 39.27	121 50.51	2.8					
36 39.50	121 50.41	2.8					
36 39.71	121 50.30	2.8					
36 39.93	121 50.18	2.8					
36 40.14	121 50.06	2.7	current noted				
36 40.36	121 49.96	2.9					
36 40.55	121 49.84	2.9					
36 40.69	121 49.76	3					

Data recorded at 5 min. intervals

APPENDIX I
NAVIGATION LOGS
FEBRUARY 24, 1992

line 1				comments	line 2				comments
lat	long	Boat Speed knots			lat	long	Boat Speed knots		
36 40.64	121 49.42	3			36 37.89	121 50.90	3		
36 40.41	121 49.43				36 38.13	121 50.83	3		
36 40.17	121 49.55	3			36 38.39	121 50.78	3		paper change
36 39.92	121 49.70	3			36 38.39	121 50.77	2.9		
36 39.82	121 49.85	3			36 38.44	121 50.77	2.9		back on line
36 39.67	121 49.98	3.3			36 38.68	121 50.66	2.9		
36 39.43	121 50.10	3.1			36 38.96	121 50.57	2.9		
36 39.20	121 50.23	2.9	boat slowed		36 39.83	121 50.48	3.1		
36 38.98	121 50.38	3.1			36 39.48	121 50.39	3.1		
36 38.73	121 50.49	3.2			36 39.72	121 50.25	3		
36 38.46	121 50.53	3.2			36 39.98	121 50.20	3.2		
36 38.39	121 50.61	3			36 39.98	121 50.10	3.2		
					36 40.21	121 49.96	3.2		
					36 40.45	121 49.79	3.2		
					36 40.69	121 49.65	3.2		
					36 40.82	121 49.50	3.2		

line 3				comments	line 4				comments
lat	long	Boat Speed knots			lat	long	Boat Speed knots		
36 40.70	121 49.60	3.3			36 37.93	121 51.01	3		
36 40.42	121 49.74	3.3			36 37.19	121 50.94	3		
36 40.17	121 49.87	3.3			36 38.45	121 50.88	3		
36 39.91	121 49.98	3.3			36 38.74	121 50.77	3.2		
36 39.68	121 50.06	3.3			36 38.99	121 50.71	3.2		
36 39.43	121 50.20	3	boat slowed		36 39.25	121 50.60	3		
36 39.79	121 50.33	3.3			36 39.51	121 50.56	3		
36 38.95	121 50.45	3.3			36 39.79	121 50.45	3.1		
36 38.69	121 50.56	3.1			36 40.06	121 50.31	3.2		
36 38.43	121 50.73	3.2			36 40.31	121 50.20	3.4		
36 38.17	121 50.86	3.2			36 40.54	121 50.03	3.1		
36 37.91	121 50.95	3.3			36 40.78	121 49.88	3.1		

Data recorded at 5 min. intervals

APPENDIX I
NAVIGATION LOGS
APRIL 27, 1992

line 1				line 2			
latt	long	Boat Speed knots	comments	lat	long	Boat Speed knots	comments
36 38.33	121 50.48	3		36 40.70	121 49.47	3	
36 38.57	121 50.39	3		36 40.45	121 49.59	3	
36 38.87	121 50.27	3		36 40.20	121 49.70	3	
36 39.05	121 50.15	3		36 39.95	121 49.81	3	
36 39.30	121 50.03	3		36 39.70	121 49.94	3	
36 39.54	121 49.92	3		36 39.45	121 50.09	3	
36 39.79	121 49.81	3		36 39.21	121 50.20	3	
36 40.01	121 49.68	3.1		36 38.95	121 50.31	3	
36 40.24	121 49.57	3		36 38.71	121 50.41	3	
36 40.49	121 49.47	3		36 38.45	121 50.53	3	
36 40.70	121 49.37	3		36 38.18	121 50.64	3	
				36 38.08	121 50.68	3	

line 3				line 4			
lat	long	Boat Speed knots	comments	lat	long	Boat Speed knots	comments
36 37.84	121 50.91	3		36 40.69	121 49.83	3	
36 38.09	121 50.87	3		36 40.45	121 49.99	3	
36 38.35	121 50.78	3		36 40.24	121 50.13	3	
36 38.63	121 50.75	3		36 39.98	121 50.22	3	
36 38.90	121 50.67	3		36 39.75	121 50.32	3	
36 39.15	121 50.59	3	off line	36 39.53	121 50.41	3	
36 38.33	121 50.75	3	back on line	36 39.27	121 50.50	3	
36 38.58	121 50.72	3		39 39.05	121 50.61	3	
36 38.82	121 50.66	3		36 38.82	121 50.71	3	
36 39.06	121 50.55	3		36 38.57	121 50.80	3	
36 39.30	121 50.43	3		36 38.34	121 50.88	3	
36 39.52	121 50.30	3		36 38.08	121 50.98	3	
36 39.76	121 50.19	3		36 37.92	121 51.04	3	
36 39.99	121 50.05						
36 40.23	121 49.92						
36 40.47	121 49.78						
36 40.68	121 49.66	3					

line 5			
lat	long	Boat Speed knots	comments
36 37.87	121 51.11	3	
36 38.10	121 51.03	3	
36 38.34	121 50.94	3	batt dead

Data recorded at 5 min. intervals

APPENDIX I
NAVIGATION LOGS
June 22, 1992

line 1			Boat Speed	
	latt	long	knots	comments
36	40.88	121 49.79	2.5	
36	40.03	121 49.75	2.9	
36	40.51	121 49.90	2.7	
36	40.25	121 49.83	2.8	
36	39.89	121 49.94	2.9	
36	39.73	121 50.06	2.8	
36	39.60	121 50.12	2.8	
36	39.46	121 50.18	2.9	
36	39.37	121 50.22	2.9	begin feature
36	39.21	121 50.28	2.8	
36	39.06	121 50.33	2.9	
36	38.98	121 50.38	2.9	
36	38.90	121 50.43	2.8	end feature
36	38.86	121 50.43	2.8	
36	38.78	121 50.48	2.6	turning
36	38.99	121 50.31	2	turning
36	38.24	121 50.25	0	
36	39.31	121 50.24		divers in
36	39.30	121 50.23		
36	38.97	121 50.37	0	divers in

Data recorded at 5 min. intervals

APPENDIX II

from Coastal Data Information Program
U.S. Army corps of Engineers and
California Department of Boating and Waterways

Spectral plots have are provided to indicate periods of interest and have no scale. All of the information was recorded at the Marina Array.

APPENDIX II

APPENDIX II

APPENDIX II

WAVE ENERGY SPECTRA FEB 1992

APPENDIX II

WAVE ENERGY SPECTRA MAR 1992

APPENDIX II

WAVE ENERGY SPECTRA APR 1992

APPENDIX II

WAVE ENERGY SPECTRA MAY 1992

APPENDIX II

WAVE ENERGY SPECTRA JUN 1992