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Sediment distribution and transport along a rocky, embayed coast: Monterey Peninsula and Carmel Bay, California

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Abstract

Field measurements of beach morphology and sedimentology were made along the Monterey Peninsula and Carmel Bay, California, in the spring and summer of 1997. These data were combined with low-altitude aerial imagery, high-resolution bathymetry, and local geology to understand how coastal geomorphology, lithology, and tectonics influence the distribution and transport of littoral sediment in the nearshore and inner shelf along a rocky shoreline over the course of decades. Three primary modes of sediment distribution in the nearshore and on the inner shelf off the Monterey Peninsula and in Carmel Bay were observed. Along stretches of the study area that were exposed to the dominant wave direction, sediment has accumulated in shore-normal bathymetric lows interpreted to be paleo-stream channels. Where the coastline is oriented parallel to the dominant wave direction and streams channels trend perpendicular to the coast, sediment-filled paleo-stream channels occur in the nearshore as well, but here they are connected to one another by shore-parallel ribbons of sediment at depths between 2 and 6 m. Where the coastline is oriented parallel to the dominant wave direction and onshore stream channels are not present, only shore-parallel patches of sediment at depths greater than 15 m are present. We interpret the distribution and interaction or transport of littoral sediment between pocket beaches along this coastline to be primarily controlled by the northwest-trending structure of the region and the dominant oceanographic regime. Because of the structural barriers to littoral transport, peaks in wave energy appear to be the dominant factor controlling the timing and magnitude of sediment transport between pocket beaches, more so than along long linear coasts. Accordingly, the magnitude and timing of sediment transport is dictated by the episodic nature of storm activity.

Keywords: Rocky coastline; Sediment distribution; Shoreface morphology; Sediment transport

1. Introduction

The coastal mountains, seacliffs, and small pocket beaches along much of California's shoreline sharply contrast with the broad, low relief depositional coastal plains, barrier islands, and long sandy beaches along much of the Atlantic and Gulf coasts of the United States. Along emergent shorelines, the presence of rocky headlands between adjacent pocket beaches disrupts wave-induced longshore sand transport or 'littoral drift' in the surf zone. Therefore, the alongshore transport of littoral sediment along rocky coasts requires a cross-shore sediment exchange and

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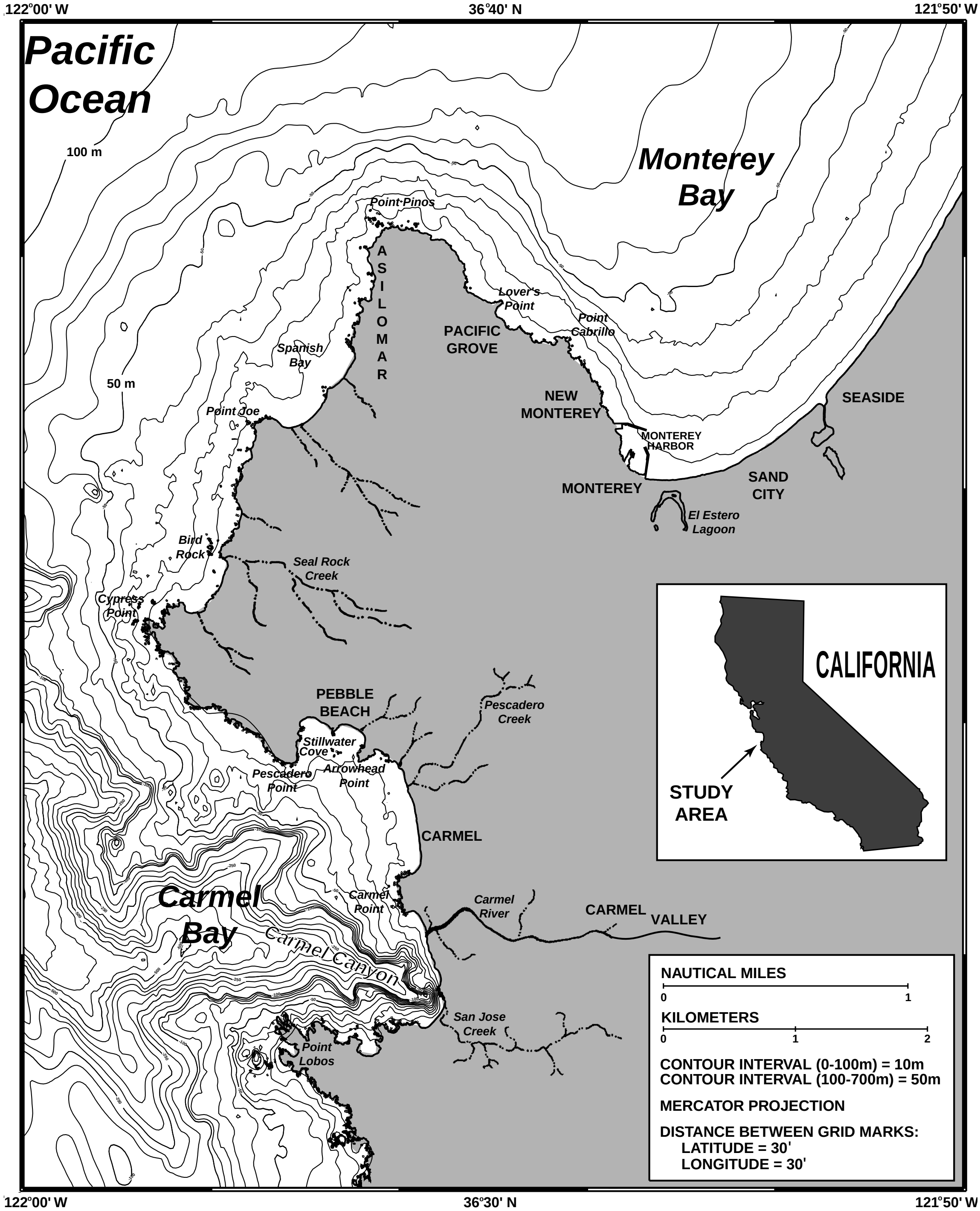


Fig. 1. Map of the Monterey Peninsula and Carmel Bay displaying the widely varying exposures and bathymetry along this section of central California which cause substantial wave energy gradients to develop. Also, note the lack of a discernable continental shelf south of Point Piños. Bathymetry by the National Oceanographic and Atmospheric Administration (1998).

alongshore transport outside of the surf zone to bypass the intervening headlands (Tait, 1995). The majority of research on the transport of littoral sediment outside the surf zone has focused on continuous low-lying sandy coasts having few barriers to extensive coast-wise migration of sand (Howard and Birkemeier, 1987; Birkemeier et al., 1989; Lee and Birkemeier, 1993). Even in these relatively sediment-rich systems, the influence of the underlying geology and bathymetry often has been cited as a possible cause for the difference between model results and what is observed in the nearshore and shallow offshore (Pilkey and Thieler, 1992; Pilkey et al., 1994). This geologic control has been shown to be significant in the 'communication' or interaction via sediment transport between adjacent embayed or pocket beaches along the rocky coastline of southeastern Australia (Wright, 1987).

Approximately 500 km (28%) of California's coast, and much of the remaining Pacific Ocean's coastline as well, is characterized by uplifted, rocky shorelines along tectonically active margins. The morphology of these shorelines includes coastal mountains, seacliffs, and small pocket beaches typically at stream mouths. The region offshore central and northern California is generally sediment-deficient, with bedrock commonly cropping out on the inner shelf (Cacchione et al., 1984, 1987; Tait et al., 1992; Tait, 1995; Anima et al., 1997). Bathymetric variations on the inner shelf along this area commonly mirror the onshore topography, with headlands typically extending offshore as barren, bathymetric highs and pocket beaches or coastal stream valleys fronted by more gently sloping bathymetric depressions. The studies by Anima and Tait also have shown that substantial volumes of littoral sediment are stored in these depressions at shallower depths whereas finer sediment commonly is observed farther offshore. Tait (1995) observed relief on the order of 0.1–10 m between these rocky highs and adjacent sediment-filled basins along northern Santa Cruz County, California. Headlands and submerged bedrock ridges can steer and focus currents, affect the direction of sediment transport, and form barriers to the alongshore transport of sediment in a manner not commonly observed along coastal plain shorelines. These kinds of coasts, common to areas of tectonic uplift and glaciostatic rebound, therefore, pose significant problems to modeling nearshore hydrodynamics and littoral transport.

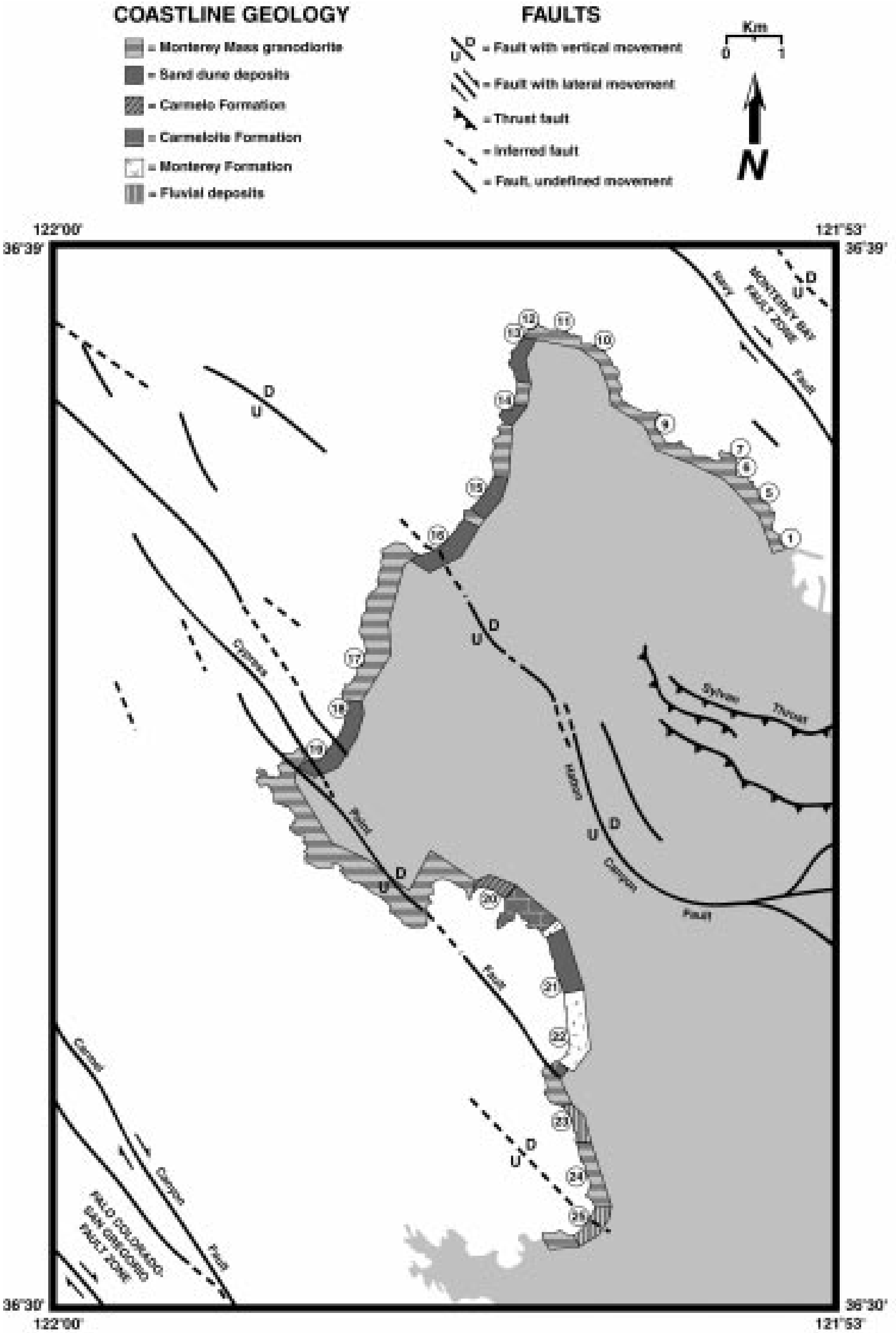
Along rocky coastlines, where sediment cover is generally thin to non-existent and the bathymetry is highly variable, the distribution of littoral sediment on the shoreface provides important information regarding not only the sources of the sediment, but also the modes and pathways of transport. Therefore, in order to accurately determine the source and transport paths of littoral sediment along rocky coastlines, it is necessary to understand the relationships between the bathymetry, geology, and sediment distribution both on the inner shelf and in the nearshore so that the intrinsic controls on sediment transport can be determined.

The beaches and nearshore along the Monterey Peninsula and Carmel Bay exhibit over a 180° range in orientation, generally have a very thin to non-existent sediment cover, and vary markedly in texture and mineralogy. These factors facilitate the interpretation of sediment origin, transport pathways within and out of the littoral system, and the role of waves in shaping the coast. The purpose of our investigation was to understand the extent of which local bathymetry, lithology, and geologic structure control the distribution and transport of littoral sediment in the nearshore and inner shelf along a rocky shoreline over intermediate (10^1–10^3 yr) time-scales.

2. Setting

2.1. Geology

The Monterey Peninsula is a roughly northeast–southwesterly trending rectangular promontory (26 km NE–SW by 18 km NW–SE) that defines the southwestern corner of Monterey Bay on the central Californian coast (Fig. 1). The central coast of California is a complex region traversed by numerous faults that together form the boundary between the North American and Pacific plates. Greene (1977), Greene and Clark (1979), and the US Army Corps of Engineers (1985) summarize much of the work on the tectonics of the study area which are summarized here. The Monterey Peninsula and Carmel Bay are intersected by several faults that generally trend northwest, parallel to the San Andreas Fault System


COASTLINE GEOLOGY
= Monterey Mass granodiorite
= Sand dune deposits
= Carmelo Formation
= Carmeloite Formation
= Monterey Formation
= Fluvial deposits
FAULTS
= Fault with vertical movement
= Fault with lateral movement
= Thrust fault
= Inferred fault
= Fault, undefined movement
Km
0 1
N
122°00'
121°53'
36°39'
36°30'
MONTEREY BAY FAULT ZONE
Navy Fault
Cypress Point Fault
Hatton Canyon Fault
Sylvan Thrust
Carmel Canyon Fault
PALO COLORADO-SAN GREGORIO FAULT ZONE

(SAFS) in accord with the regional structure (Fig. 2). The right-lateral transform movement along the SAFS has strongly influenced not only the topography and bathymetry, but also the distribution of rock types and thus the sources of littoral sediment. The orientation of the shoreline is primarily controlled by extension of the crustal block due to shear along the faults within the Monterey Bay Fault Zone to the east and the Palo Colorado–San Gregorio Fault Zone to the west. The lesser faults between these two fault zones tend to be downthrown to the northeast and uplifted to the southwest, causing a staircase-like topography that, in conjunction with the orientation of joints and other structural weaknesses, established the primary drainage pattern observed today.

The Santa Lucia block is composed of lower Upper Cretaceous, highly fractured, Monterey Mass granodiorite porphyry of the Salinian Block (Ross, 1979) that crops out along the length of the peninsula's shoreline and in the offshore (Fig. 2). Unconformably overlying this granodiorite includes the marine sandstone with igneous and metamorphic conglomeritic lenses of the Paleocene Carmelo Formation, a submarine canyon deposit; unconformably overlying this unit are the arkosic and conglomeritic, nonmarine red beds and interbedded sandstones of the lower Miocene Temblor Formation and the transgressive siliceous deep marine mudstone of the middle Miocene Monterey Formation. Unconformably overlying these formations are the time-transgressive upper Miocene to Pliocene Santa Margarita Sandstone, a shallow water deposit, and the Pliocene Paso Robles Formation, a deeper water siliceous mudstone (Greene and Clark, 1979; Chin et al., 1993).

Upper Pleistocene eolian sands and Holocene marine terrace deposits are exposed in many areas along the Monterey Bay coastline (Dupre, 1990; Chin et al., 1993). Terrace deposits are generally composed of poorly sorted sand and gravel, whereas the Holocene alluvium includes unconsolidated stream channel, levee, floodplain, terrace, fan, mudflow, and landslide deposits. The cliffs that back the small beach along the eastern half of Stillwater Cove are composed of the easily eroded Carmelo Formation; in contrast Arrowhead Point, at the southeastern end of Stillwater Cove is composed of resistant volcanics of the Tertiary Carmeloite Formation. At the northern end of Carmel Beach there are also large (>20 m high) late Pleistocene sand dunes (Chin et al., 1993), whereas the central and southern portions of the beach are backed by a low (~8 m) cliff composed of the erodable Monterey Formation.

Griggs and Savoy (1985) calculated 60 yr seacliff erosion rates for the peninsula from aerial photograph interpretation. They calculated the erosion rates to be less than 3 cm/yr for more than 90% of the peninsula except in the area of highly developed Monterey waterfront, where the erosion rates were greater than 60 cm/yr. Thus, the majority of the peninsula is relatively resistant to erosion and produces a very limited supply of littoral sand.

2.2. Coastal and nearshore geomorphology

Like most coastal areas in California, the geomorphic character of the Monterey Peninsula and Carmel Bay is largely a product of local structure and bedrock lithology. Along the peninsula there is a spectrum of coastline morphologies, including steep seacliffs, narrow pocket beaches backed by coastal and fluvial terraces and bounded by resistant headlands, and long stretches of wide, sandy beaches backed by dune fields and marine terraces. Numerous steep perennial streams drain the peninsula during the winter rainy season and contribute the vast majority of the total input of sediment to the coastal zone (Hicks, 1985; Best and Griggs, 1991). These streams incise the terraces and a few of them terminate in ephemeral sloughs that back some of the beaches along the western portion of the peninsula. At present, the majority of streams flow northwest along the western part of the peninsula, south into Stillwater Cove, or

Fig. 2. The location of major faults and coastline compositions in the study area relative to the beaches investigated. The northwest trend of the faults is controlled by the San Andreas Fault System which has dictated the fracture patterns and drainages along the peninsula. The downthrown southwest and upthrust northeast sides of the faults that display predominantly vertical motion has created a staircase-like topography along the peninsula. This morphology has denied major drainages access to the southern section of the peninsula between Cypress and Pescadero Points. Modified after Greene (1977), Chin et al. (1993) and Clark et al. (1997). The circled numbers denote the location of beaches studied (see Table 1).

westward into Carmel Bay. Many of the paleo-drainages along the northern part of the peninsula in the area of Pacific Grove and Monterey no longer carry significant discharge or sediment due to the heavy road and building construction in the area. We inferred the locations of these channels from examination of topographic maps, aerial photography, and field observations.

The shoreline of the Monterey–Carmel region can be divided into three principal geomorphic regions. The northern shoreline, stretching from Monterey Harbor in the north to Cypress Point (Fig. 1), is characterized by rocky headlands and small pocket beaches, some of which are backed by dune fields or a low (<6 m high) marine terrace (Dupre, 1990). The thicker sediment cover offshore of the harbor consists of fine sand (Bascom, 1951; Wolf, 1970) that gives way to less abundant coarser sand and granite outcrops from Point Cabrillo to Point Piños (Galliher, 1932; Dorman, 1968; Greene, 1977). Galliher (1932) interpreted the offshore sediment to be sparse, thin sheets of coarse-grained sediment between outcrops along the western part of the peninsula between Point Piños and Cypress Point. The section of coastline between Cypress Point and Stillwater Cove (Fig. 1) is very rugged with high (>30 m) seacliffs composed of porphyritic granodiorite; no significant protected coves or beaches are observed along this section of the peninsula. The southern shoreline, extending south from Arrowhead Point to Monastery Beach at the mouth of San Jose Creek (Fig. 1), is composed of wide, sandy beaches that are more or less continuous except in the area of Carmel Point and are backed by a low marine terrace. The shelf along this section of the study area has a continuous sediment cover and is deeply incised by the Carmel Canyon and less deeply incised branches of the Carmel Canyon extend northeast in the direction of Stillwater Cove and just to the north of Carmel Point.

2.3. Oceanography and hydrodynamics

The waves that approach the Monterey Peninsula and Carmel Bay are characterized by three dominant modes. The northern hemisphere swell is typically generated by cyclones in the north Pacific during the winter months (November–March) and can attain deep-water wave heights exceeding 8 m. The southern hemisphere swell is generated by storms in the Southern Ocean during summer months and, although they generally produce smaller waves than the northern hemisphere swell, they often have very long periods (>20 s). Local wind-driven seas typically develop rapidly when low pressure systems track near central California in the winter months or when strong sea breezes are generated during the spring and summer (National Marine Consultants, 1960; Meteorology International Inc., 1977). These winds typically come out of the northwest; Galliher (1932) concluded from dune orientations that this vector is the dominant wind mode that impinges on the shoreline of the peninsula.

Storms tend to approach this area from the northwest, west, and southwest during the winter months (Bixby, 1962). The dominant northwest swell causes the waves to generally strike the shoreline between Point Piños and Cypress Point and along southern Carmel Bay relatively unimpeded and unrefracted. The waves that approach the shoreline between Monterey Harbor and Point Piños tend to refract around Point Piños and thus lose energy whereas the beaches along Stillwater Cove and Carmel Beach are protected by the refraction around Cypress Point (Wiegel, 1964).

3. Methods

Our investigation into the influence of geology and coastal morphology on sediment distribution and transport along a rocky shoreline encompassed two primary tasks. The first was to document the geomorphic character of the beaches and the physical and mineralogic properties of the sediment in the study area. The second was to map the distribution of littoral sediment and bedrock in the nearshore and on the inner shelf. The morphologic study of the beaches included measuring: (a) beach planform dimensions; (b) beachface and nearshore slope; (c) beach orientation with respect to the dominant wave direction; (d) modal morphodynamic state as defined by Wright and Short (1984); and (e) relative wave energy at each of the beaches (Table 1). Beach and shoreface slope were evaluated subaerially from qualitative observations and quantitatively using the shoreline and the 20 m isobath, respectively. The

Table 1
Morphologic and hydrodynamic properties of the beaches (see Fig. 2 for site locations)

Site #	Beach name	Mean width (m)	Length (m)	Exposure (degrees)	Shoreface slope[a]	Mean relative wave height[b] (m)	Modal beach state[c]
1	San Carlos	24	166	357	0.120	0.3	Intermediate
5	MacCaby	12	119	002	0.138	1.0	Intermediate
6	Monterey Aquarium	25	150	020	0.120	1.7	Intermediate
7	Hopkins Marine Station	32	43	043	0.143	1.7	Reflective
9	Lover's Point	30	95	058	0.051	1.0	Reflective
10	Lucas Point	18	127	307	0.102	0.3	Intermediate
11	Ocean View	30	103	296	0.120	2.3	Reflective
12	Point Piños (east)	20	87	315	0.102	3.0	Reflective
13	Point Piños (west)	20	40	228	0.080	2.3	Reflective
14	Asilomar	24	75	285	0.051	2.3	Intermediate
15	Spanish Bay	44	665	306	0.042	3.0	Dissipative
16	Moss	25	539	319	0.045	3.0	Dissipative
17	Bird Rock	26	143	274	0.065	3.0	Dissipative
18	Seal Rock	100	127	253	0.072	2.3	Dissipative
19N	Fan Shell (north)	33	119	319	0.060	2.3	Dissipative
19S	Fan Shell (south)	40	55	326	0.051	3.0	Intermediate
20	Stillwater Cove/Pebble	45	428	212	0.072	0.3	Intermediate
21	Carmel (north)	105	1180	272	0.060	1.0	Intermediate
22	Carmel (south)	70	705	317	0.060	1.7	Dissipative
23	Carmel River (north)	57	610	242	0.120	2.3	Reflective
24C	Carmel River (central)	52	87	254	0.237	2.3	Intermediate
24S	Carmel River (south)	48	269	266	0.281	1.7	Reflective
25	Monasterey	50	586	334	0.360	3.0	Reflective

[a] Calculated using shoreline and 20 m isobath.
[b] From the Coastal Data Information Program (1998) Monterey Bay refraction/shoaling model with the most commonly observed conditions for the study area (direction = 315°, deepwater wave height = 2 m, and period = 12 s).
[c] Estimated from observations of oceanographic conditions and beach morphology over 4 months according to Wright and Short (1984).

relative wave energy off the beaches was evaluated using observations from the Coastal Data Information Program's (1998) Monterey Bay refraction/shoaling model assuming the dominant incident wave direction for the central coast of California. This direction was determined using 4 yr of directional wave data (>12 000 observations) from the Coastal Data Information Program's (1998) Point Reyes buoy from which the Monterey Bay refraction/shoaling model was initialized. These data encompass a range of conditions, including an average winter (1996–1997), a La Niña winter (1995–1996), and an intense El Niño winter (1997–1998) in order to give a representative range of wave directions.

Littoral sediment samples were collected approximately every 10 m alongshore in the swash zone for the 21 sandy beaches; the other four beaches (Sites 2–4 and 8, Fig. 2) are characterized by greater than 75% by mass of boulder-size (−8 ϕ) material and were not sampled. Samples collected exemplify the swash zone species of Liu and Zarillo (1989) and were therefore interpreted to represent the coarsest sediment fractions to be found along the beaches' cross-shore profiles. This sampling method provided representative textural and mineralogic properties for each beach by averaging the alongshore variations that typically occur on beaches. The samples were sieved and then mean grain size, sorting, and skewness were calculated according to Folk and Ward (1957) and are displayed in Table 2. Mineralogy was evaluated by determining the percentage of quartz, feldspathic, heavy (Fe- and Mg-rich, such as hornblende and biotite with lesser magnetite and augite) mineral grains, and shell material from 100 sand-size grains in the 0–3 ϕ range using a petrographic microscope (Table 2). Percentages were rounded to the nearest 5% to compensate for any differentiation during the splitting of the samples.

Table 2
Textural and mineralogic properties of the littoral sediments (see Fig. 2 for site locations; note: all mineralogic distributions are % by mass of a 50–100 g sample rounded to the nearest 5%)

Site #	Beach name	Mean (ϕ)	Sorting (ϕ)	Skewness (ϕ)	Quartz (%)	Feldspars (%)	Heavy minerals[a] (%)	Shell material (%)
1	San Carlos	1.62	0.77	0.31	80	10	10	< 5
5	MacCaby	0.56	0.65	0.61	65	25	10	< 5
6	Monterey Aquarium	2.01	0.67	1.21	50	40	10	< 5
7	Hopkins Marine Station	0.05	1.21	−0.19	40	20	10	30
9	Lover's Point	0.05	1.09	−0.03	40	50	10	< 5
10	Lucas Point	−0.05	0.85	−0.24	45	40	15	< 5
11	Ocean View	−1.56	0.53	−1.07	35	40	20	5
12	Point Piños (east)	−1.62	0.54	−0.68	30	50	20	< 5
13	Point Piños (west)	−0.87	0.86	−0.26	30	55	15	< 5
14	Asilomar	−0.23	0.56	−0.18	35	50	15	< 5
15	Spanish Bay	1.92	0.46	1.14	30	60	10	< 5
16	Moss	1.80	0.45	0.91	30	60	10	< 5
17	Bird Rock	1.68	0.45	0.79	30	60	10	< 5
18	Seal Rock	1.48	0.35	0.87	35	50	15	< 5
19N	Fan Shell (north)	1.12	0.38	0.63	35	45	20	< 5
19S	Fan Shell (south)	0.28	1.04	−0.24	35	50	15	< 5
20	Stillwater Cove/Pebble	1.74	0.42	0.94	40	30	30	< 5
21	Carmel (north)	0.57	1.92	−0.44	35	50	15	< 5
22	Carmel (south)	1.87	0.52	0.89	40	45	15	< 5
23	Carmel River (north)	0.68	0.83	0.04	60	25	15	< 5
24C	Carmel River (central)	0.96	0.82	0.40	60	30	10	< 5
24S	Carmel River (south)	−0.87	0.44	−0.56	65	30	5	< 5
25	Monasterey	−0.66	0.35	−0.43	65	30	5	< 5

[a] Iron- and magnesium-rich minerals (see text).

Historic (1949 and 1970) and modern (1990) beach widths were determined via optical comparator from 1:20 000, 1:12 000, and 1:15 840 scale vertical aerial photography, respectively (Fig. 3). Vertical video imaging (altitude ~650 m) along most of the study area was conducted by the US Geological Survey in the fall of 1997 as part a study to measure coastal change caused by the El Niño related storms predicted for the 1997–1998 winter (B.M. Richmond, USGS, unpublished Hi-8 aerial videography). This imagery was utilized, in conjunction with 1990 vertical aerial photography (±3 m spatial resolution), to map sediment distribution in the nearshore and on the shoreface (Fig. 4). The combined video imaging and aerial photography made it possible to commonly map the distribution of sediment and rock outcrops visually to water depths greater than 15 m along the Monterey Peninsula and Carmel Bay (Fig. 5). This was facilitated by the light color of the littoral sediments contrasting sharply with either the (a) dark algal covered rock outcrops, or (b) dark patches of kelp that only grow on hard substrates and, therefore serve as a proxy for rock outcrops. These observations were corroborated by surface dives at each beach and a number of scuba dives off selected beaches. Maps of sediment and rock distribution were merged with maps of onshore drainage and high-resolution bathymetry compiled by Chase (1993) to examine the relationships between the coastal morphology and sediment distribution.

4. Results

4.1. Beach morphology

The beaches along the northern part of the Monterey Peninsula from Asilomar State Beach to the Monterey Harbor tend to be narrow (~15 m) and short (<166 m in length) as shown in Table 1.

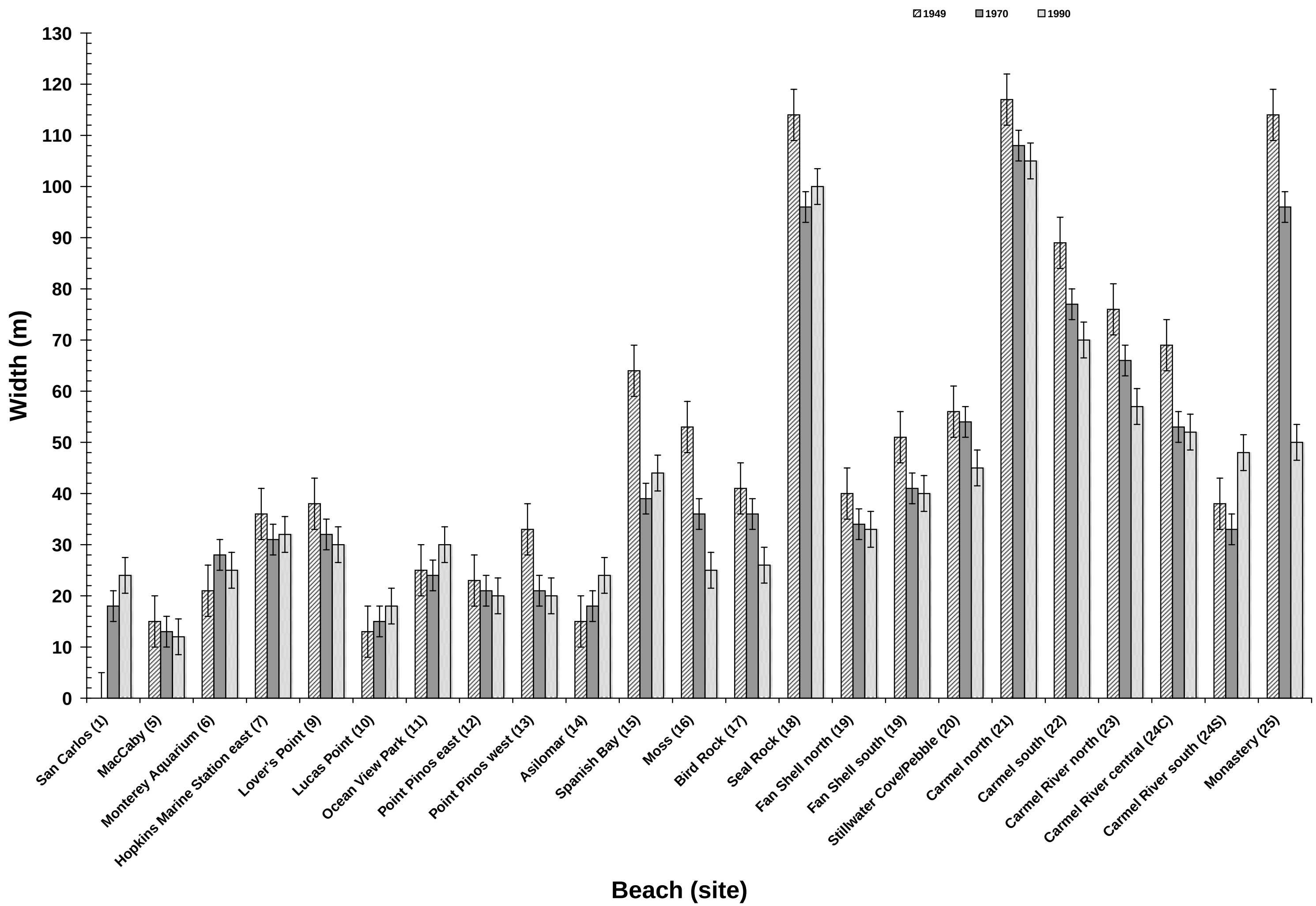


Fig. 3. Changes in beach width between 1949 and 1990 measured from aerial photography taken in the summer months. The maximum error in width is ±5 m as dictated by the 1949 1:20 000 imagery. Most of the decreases in beach width observed along the study area are interpreted to result from such anthropogenic activities as sand mining, the construction of housing and golf courses, and increased farming.

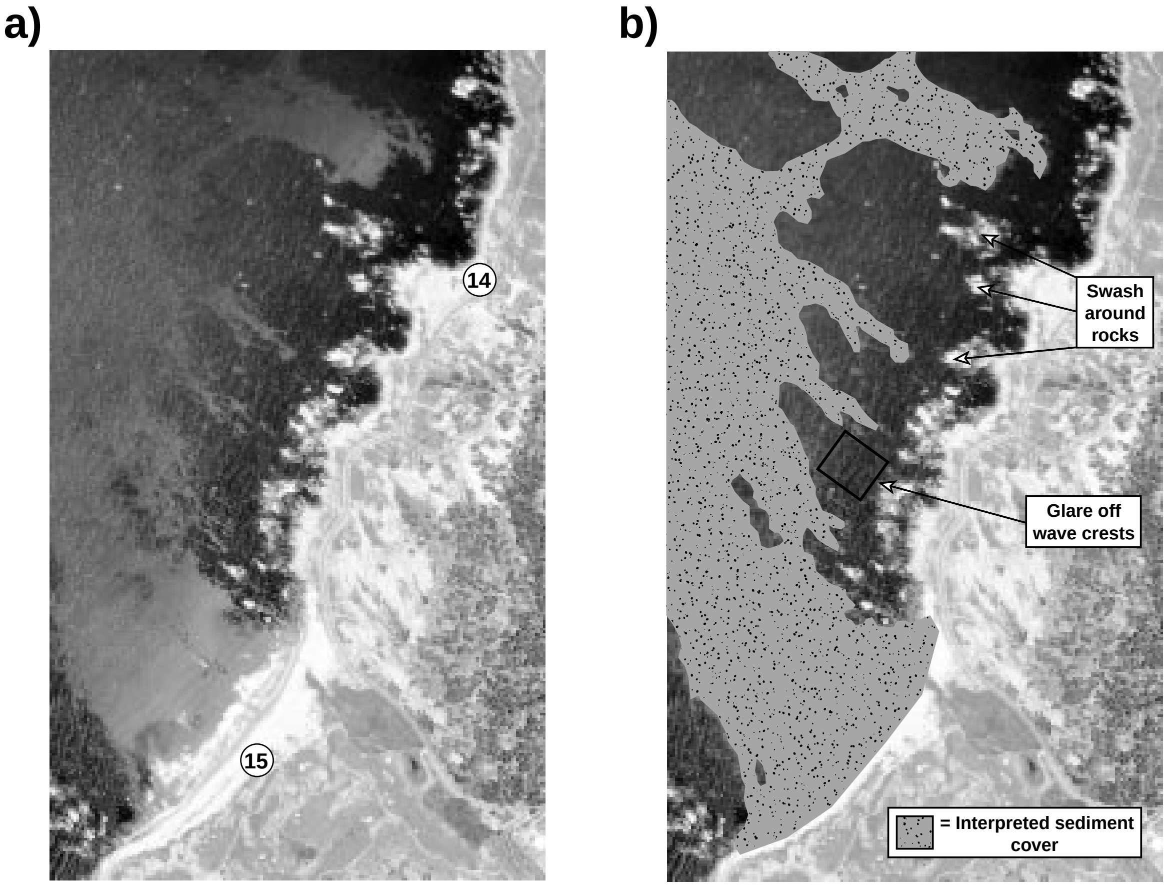
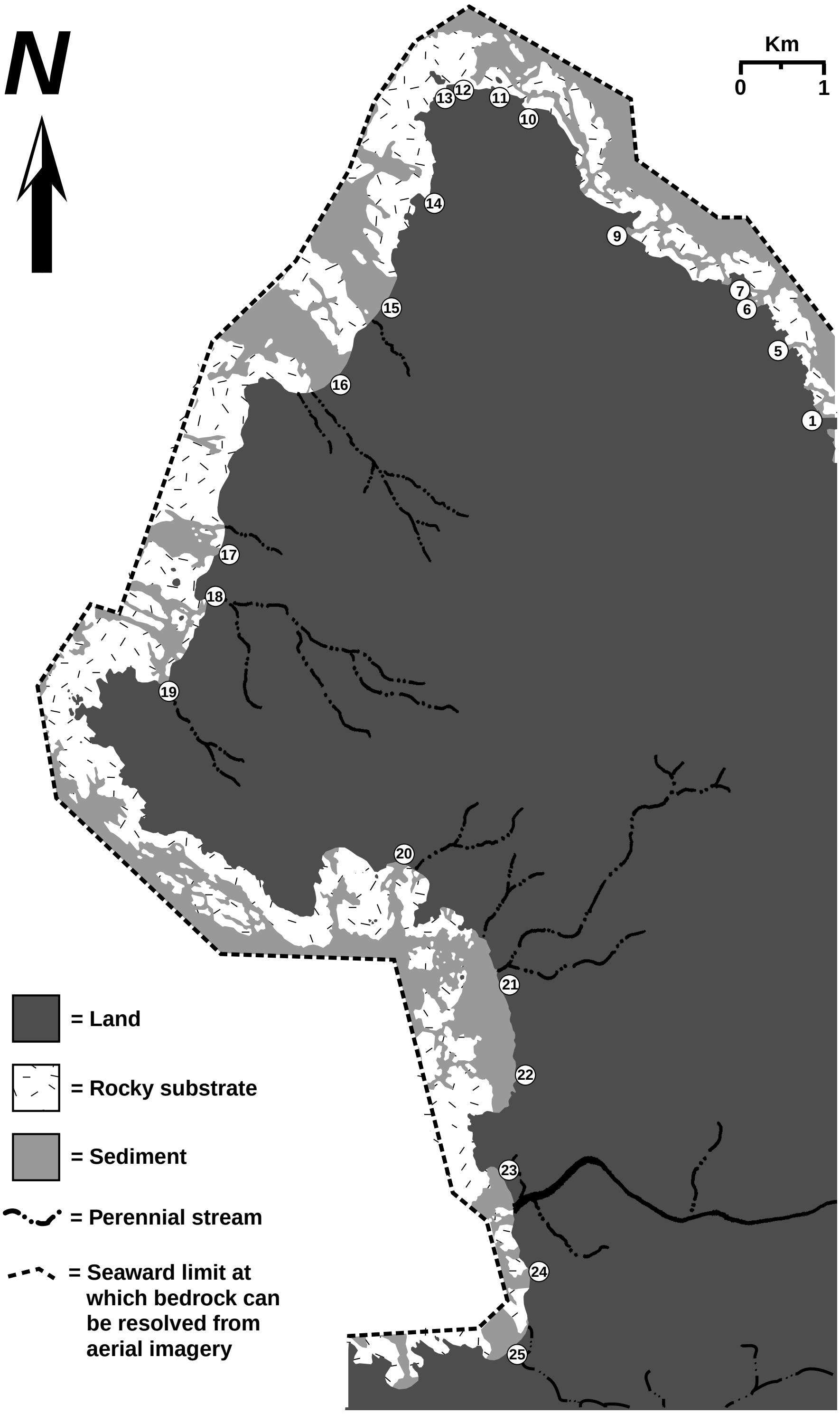


Fig. 4. Example of method used to map sediment and rock outcrops in the nearshore and on the inner shelf off Asilomar State Beach and Spanish Bay. (a) Aerial imagery with light levels and contrasts modified to delineate sediment and rock outcrops along with study site locations. (b) Interpreted sediment distribution overlying the aerial imagery.

The beaches generally are found in locations that are protected from the dominant northwest wave direction, either by offshore rocks, headlands, or engineering structures and all have intermediate to reflective modal beach states. Although most of the beaches along this section of the peninsula show no significant change in beach width over the last 40 yr, the beach just to the west of the Monterey Harbor developed from essentially no beach to its present width of 24 m following the construction of the western breakwater in 1959 (Fig. 3). The beaches along the western part of the peninsula from Spanish Bay south to Cypress Point are much wider and longer than those to the north. These beaches also tend to be more dissipative and have lower gradient shorefaces than those along the northern portion of the peninsula. The beaches south of Asilomar exhibit significant decreases in beach width over the last 40 yr, with decreases of up to 20 m (~30%) at the beaches along Spanish Bay.

Fig. 5. Distribution of sediment and bedrock in the nearshore and inner shelf along the Monterey Peninsula and Carmel Bay as resolved from the aerial imagery. Note that all of the beaches are connected to offshore sand bodies by nearly shore-parallel patches of sediment that have orientations similar to present or past drainages onshore. The circled numbers denote the location of beaches studied.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22
23
24
25
= Land
= Rocky substrate
= Sediment
= Perennial stream
= Seaward limit at which bedrock can be resolved from aerial imagery

The beach in Stilllwater Cove also displays a reduction in beach width since the late 1940s. The beach along the northwestern section of the cove, in front of the Pebble Beach Golf Course clubhouse, was covered by an engineering structure (riprap and a seawall) to protect the 17th and 18th holes of the golf course during the course of the study. The beach along the eastern portion of the cove displays an intermediate modal beach state as defined by Wright and Short (1984), being protected from northerly and westerly wave approaches by the Monterey Peninsula and southwesterly waves by Point Lobos, Pescadero Point, and a group of offshore rocks that marks the southwestern boundary of the cove. Carmel Beach, between Arrowhead and Carmel Points, grades from an intermediate modal beach state in the north to a more dissipative modal state at its southern end, mirroring the increase in wave energy to the south. This beach is wider than all other beaches investigated, except for those at Spanish Bay, and has narrowed noticeably in the last 40 yr. Carmel Beach is also the longest (nearly 2 km), most continuous beach in the study area.

Carmel River State Beach, at the mouth of the Carmel River, and Monastery Beach, at the mouth of San Jose Creek, display the greatest historical change in width observed along the study area, with Monastery Beach decreasing in width by more than 50% over the past 40 yr. These beaches are more exposed to the dominant northwest swell and are much more reflective than those in northern Carmel Bay. The shoreface slope off the beaches in southern Carmel Bay is the greatest observed along the study area due to the southern head of Carmel submarine canyon.

4.2. Sedimentary characteristics

The littoral sediment tends to grade from very coarse sand and granules at Point Piños to medium and coarse sand by the harbor, while at the same time becoming more quartzitic and less feldspathic (Table 2). Along the western section of the peninsula from Asilomar south to Cypress Point, the littoral sediment on the beaches tends to be finer (medium sand) than those to the northeast. The sediment is also better sorted and has a higher percentage of plagioclase feldspars than the sediment near the Monterey Harbor, causing the sediment to appear white in color. Even though there is a large percentage (~30% by mass) of well-rounded ferromagnetic gravel in the sediment along Stillwater Cove, the mean grain size falls close to the medium-to-fine sand transition. The sand fraction of this sediment tends to be more quartzitic and have a lower concentration of feldspars than along adjacent stretches of the coast.

Just south of Arrowhead Point, the sediment is similar to that along the western part of the Monterey Peninsula, in that it is more feldspathic in composition and lighter in color than the sediment in Stillwater Cove. The beaches along the southern part of Carmel Bay appear to be distinctly different from those in the northern part of the bay. They are composed of more mafic and quartzitic sediment than the feldspar-rich beaches to the north. The sediment also tends to coarsen to the south, and this increase in grain size is reflected in the beaches' steeper foreshore slopes.

4.3. Sediment distribution

Along the northern section of the Monterey Peninsula between the harbor and Point Piños, which is oriented roughly parallel to the dominant wave direction, nearly shore-parallel ribbons of sediment occur at depths between 2 and 6 m (Figs. 5 and 6). This section of the study area also is marked by roughly shore-normal patches of sediment connected by the shore-parallel sediment ribbons in the nearshore; at depths greater than 10 m the entire seafloor is covered by sediment. These shore-normal features tend to align with onshore drainages and typically are in depressions bounded by bedrock exposures. The shore-normal channels range in width from approximately 25 m to over 100 m; their widths roughly correlate with the drainage area of their corresponding onshore paleo-stream channels identified from the topography. Offshore Pacific Grove and New Monterey, bedrock tends to crop out either along more steeply sloping seafloor between the 5 and 15 m isobaths, offshore of headlands to depths less than 10 m, or alongshore in depths greater than 2 m. These bathymetric lows, most likely paleo-stream channels incised during periods of lower sea level, appear to be major areas for the storage of littoral sediment on the inner shelf due to their large

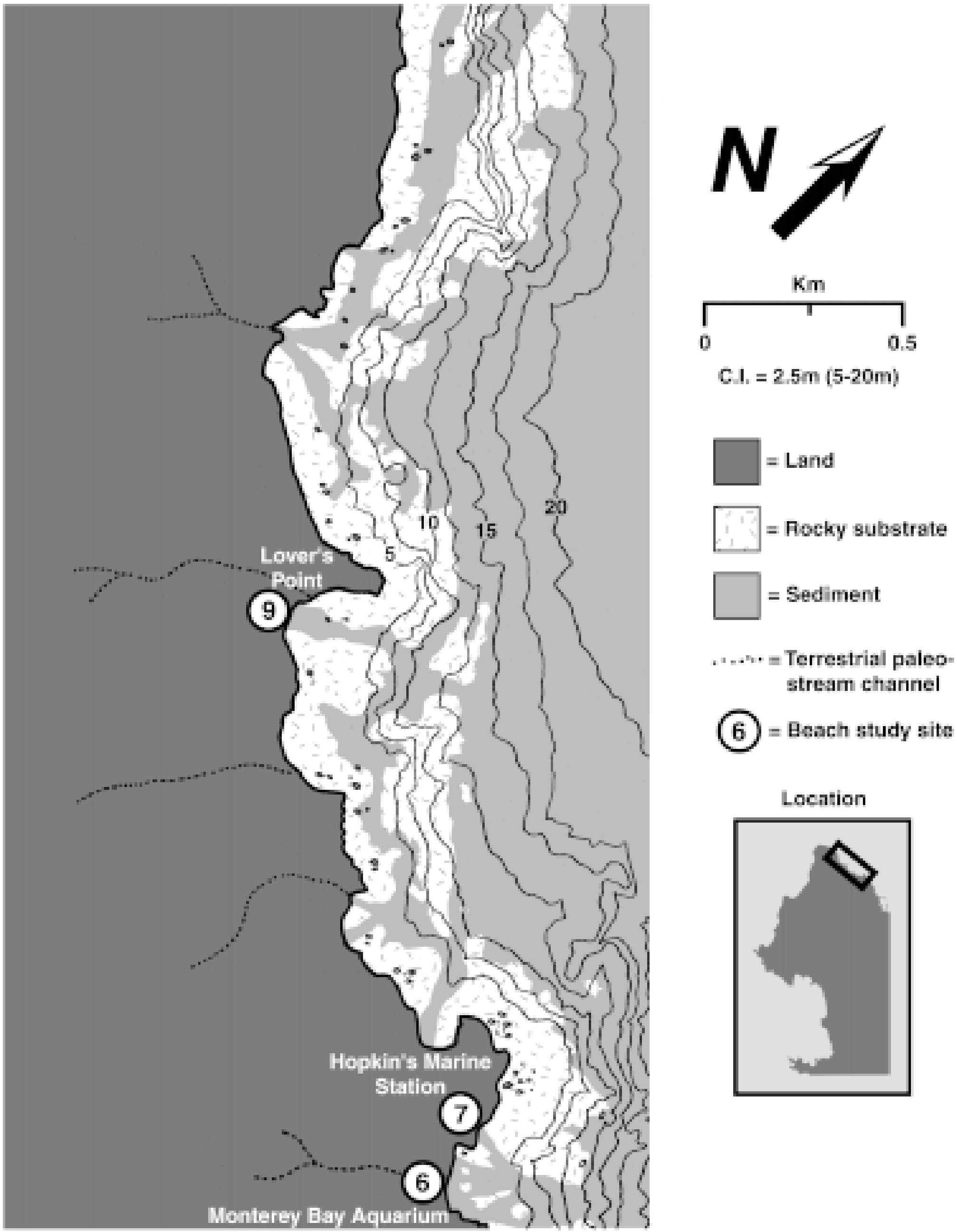


Fig. 6. Interpreted sediment distribution along the nearshore and inner shelf off Pacific Grove and New Monterey overlain with the high-resolution bathymetry by Chase (1993). The shore-parallel ribbons of sediment typically lie at a depth of 2–6 m whereas most of the shore-normal patches of sediment lie offshore of paleo-stream channels onshore.

dimensions in the study area and along the rocky coastline to the north (Tait, 1995).

The nearshore and shoreface off the peninsula between Point Piños and Cypress Point primarily display shore-normal sedimentary deposits (Figs. 7 and 8). In Spanish Bay, the two dominant channels are between 200 and 500 m wide. The greater width of these shore-normal features as compared to those off Pacific Grove and New Monterey is likely due to the substantially larger drainage areas of the streams that discharge into Spanish Bay. Tait (1995) observed this correlation between stream basin drainage area and the width of shore-normal sediment filled channels at greater depths off northern Santa Cruz County. Similar to the shoreface off Pacific Grove and New Monterey, these shore-normal features tend to align with onshore drainages and commonly occur in more gently sloping bathymetric depressions. Most waves incident upon this segment of the study area approach the shoreline in an approximately shore-normal orientation due to the local bathymetry and orientation of the coast; this section of the peninsula also is oriented roughly normal to the dominant wind direction (Galliher, 1932). In the few locations where there are shore-parallel ribbons of sediment (west of Site 16 in Fig. 7; between Sites 17, 18, and 19 in Fig. 8), these features tend to be located in depths between 2 and 6 m.

Along the southern portion of the peninsula, between Cypress Point and Pescadero Point, no streams have incised the bedrock, and the shoreline is oriented roughly parallel to the dominant wave direction. Here, sediment is generally absent both in the nearshore and on the innermost portion of the shelf (Fig. 9). There are, however, numerous deposits of sediment oriented roughly shore-parallel further out on the shelf. Although we lack high-resolution bathymetry for this section of the study area, the low-resolution bathymetry (National Oceanographic and Atmospheric Administration, 1998) indicates that these sedimentary deposits overlie a relative gently sloping sea floor in water depths greater than 15 m. The roughly shore-parallel ribbons of sediment in shallower water depths (2–6 m) along the northern part of the peninsula are absent between Cypress and Pescadero Points.

In Stillwater Cove, shore-normal patches of sediment, which correlate with onshore drainages, occur between bedrock exposures extending from the shoreline southeastward out of the cove. Along Carmel Beach, as elsewhere along the peninsula, there are shore-normal deposits of sediment similar to those to the north, with one difference being a more chaotic distribution of sediment between outcrops. A wide, continuous band of sediment in the nearshore and upper shoreface also marks this area, similar to the nearshore off Sites 11 and 12 (Fig. 5). Off Carmel River State Beach, the bottom is almost continuously covered by sediment; only offshore of the few rocky headlands are there any subaqueous rock outcrops; these outcrops are limited in spatial extent.

Therefore, three dominant sedimentary modes appear to characterize the distribution of littoral sediment along the Monterey Peninsula and Carmel Bay: (1) shore-parallel patches of sediment at depths greater than 15 m; (2) shore-parallel ribbons of sediment in shallow (2–6 m) depths connecting shore-normal sediment-filled depressions that merge at depths greater than 15 m; and (3) shore-normal sediment-filled depressions between barren rocky bathymetric highs that coalesce at depths greater than 15 m. All of this littoral sediment is situated within the depth zone for dynamic suspension and transport by wave orbital motions in southern Monterey Bay (Hunter et al., 1988) and above the 'closure depth' determined for locations to the north in Santa Cruz County (Hallermeier, 1981; Seelbach, 1993; Tait, 1995). This sediment typically is found in areas of negative relief or on more gently sloping areas that characterize the nearshore and inner shelf off most of the beaches along the study area. Most of the shore-normal patches of sediment are in depressions offshore of present or paleo-stream channels that we interpret to be the result of fluvial incision during periods of lower sea level. Shore-parallel ribbons of sediment generally are observed along sections of shoreline oriented roughly parallel to the dominant wave and wind direction either (a) at depths greater than 15 m as in Fig. 9, or (b) in a narrow zone between a depth of 2 and 6 m that is typically bounded to the offshore by more steeply sloping outcropping bedrock (Fig. 6). This shallow zone of alongshore sediment transport lies within the depth range for active bi-directional transport identified by Hallermeier (1981) and Seelbach (1993) for pocket beaches in northern Monterey Bay.

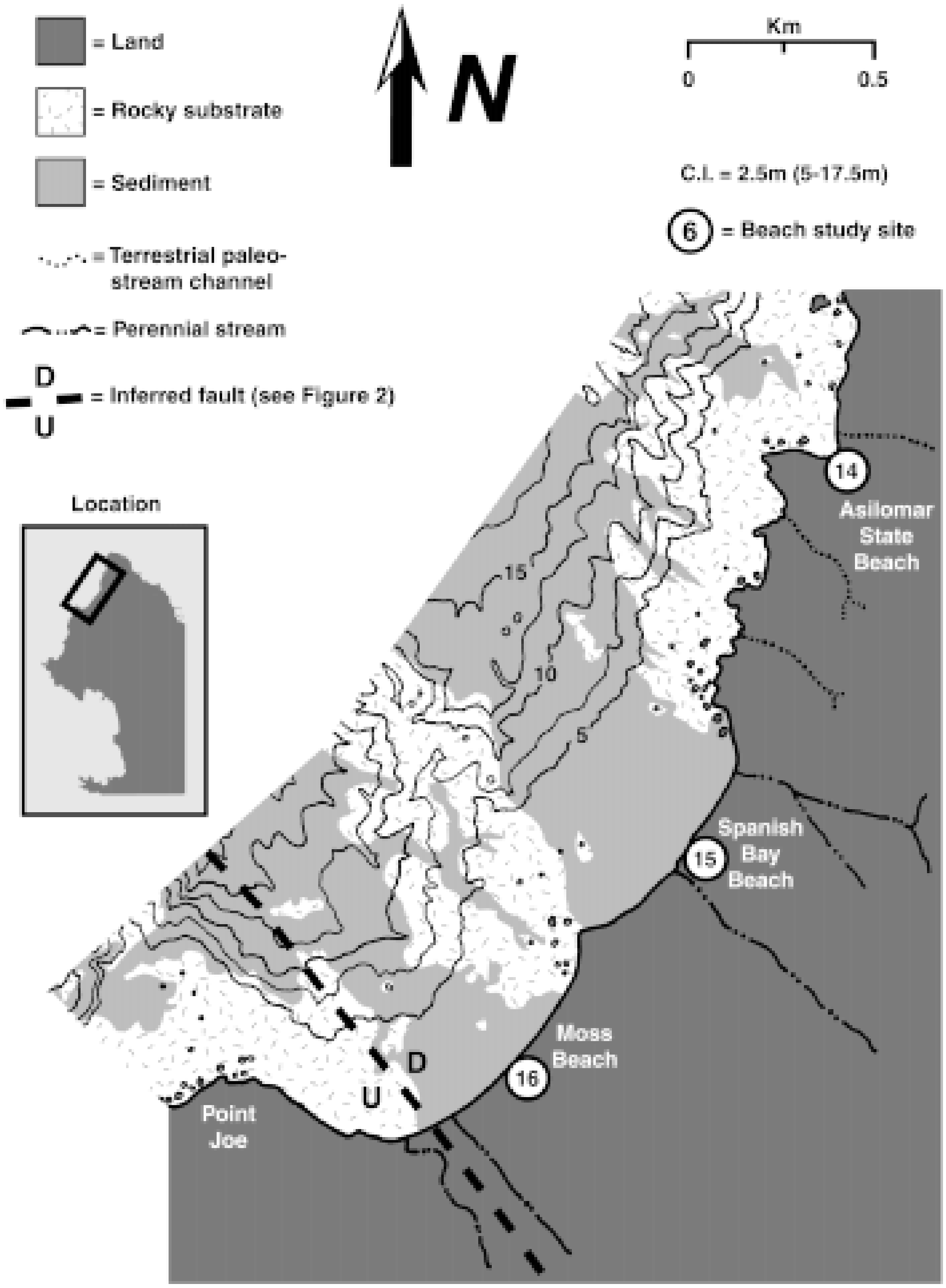


Fig. 7. Interpreted sediment distribution along the nearshore and inner shelf off Asilomar State Beach and Spanish Bay overlain with the high-resolution bathymetry by Chase (1993). The greater width of the shore-parallel channels along Spanish Bay as compared to those in Fig. 5 is likely due to the greater drainage area of streams in this area relative to those that discharge northwest into Monterey Bay. Also, note the absence of shore-parallel ribbons of sediment common along Monterey and Pacific Grove in Fig. 5.

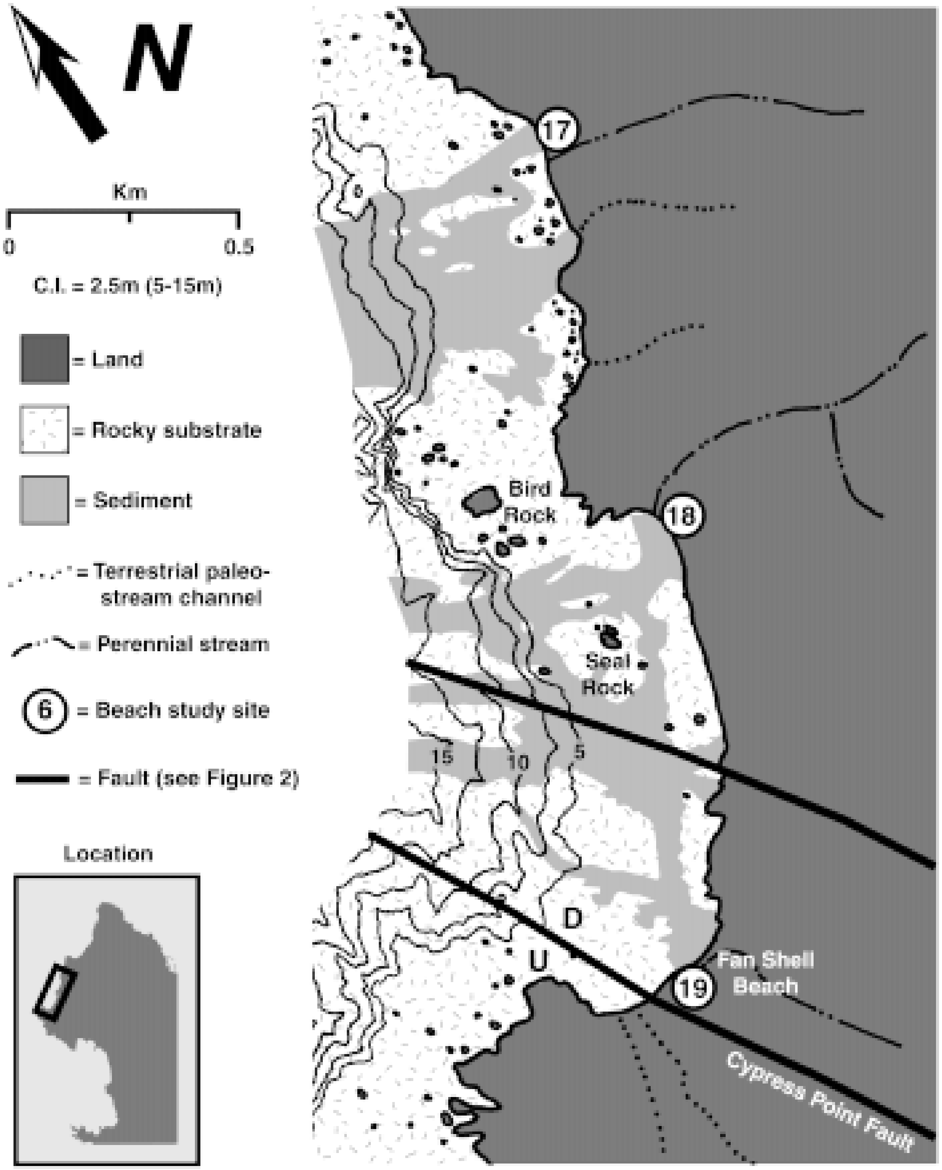
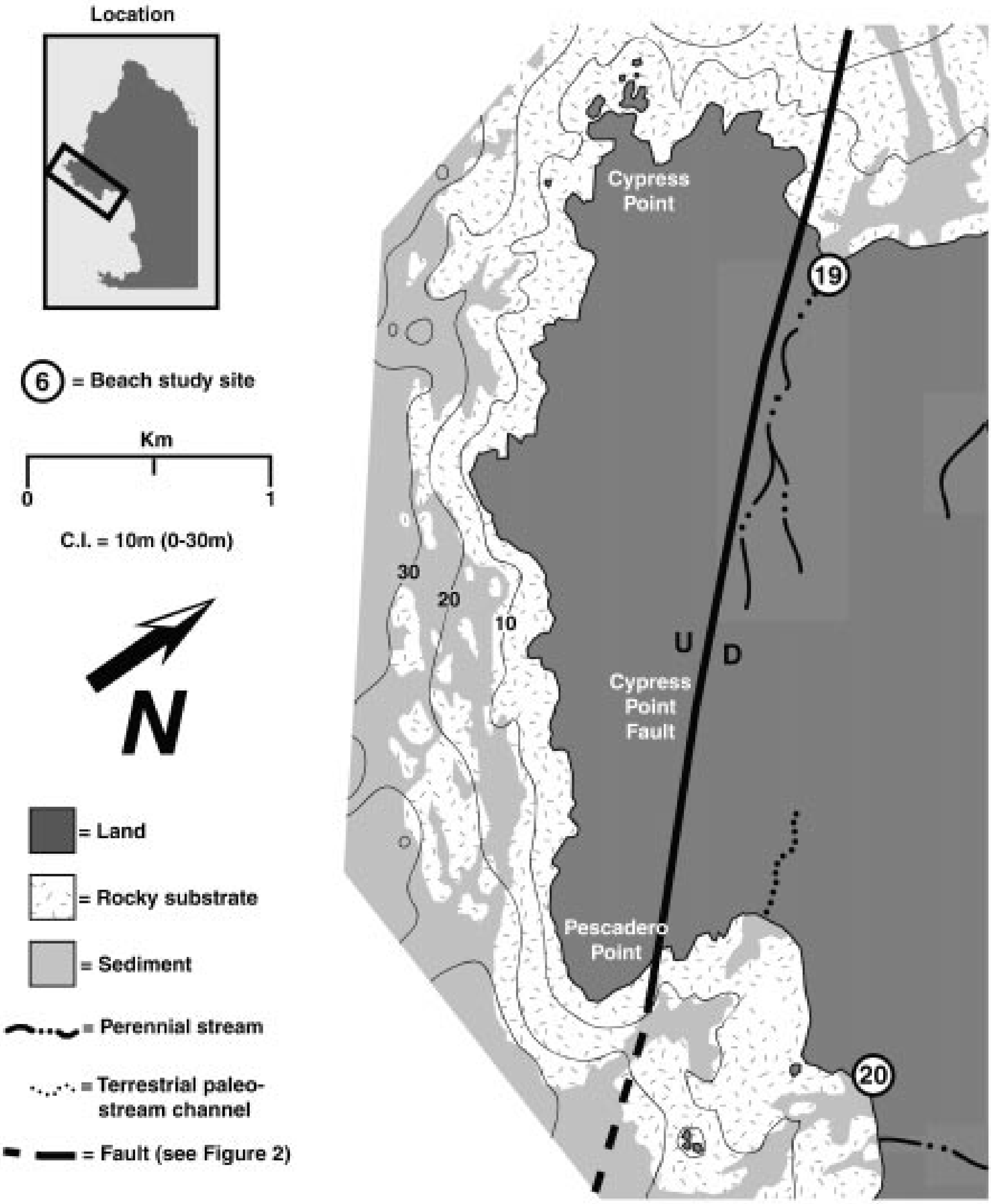


Fig. 8. Interpreted sediment distribution along the nearshore and inner shelf off the region encompassing Bird Rock, Seal Rock, and Fan Shell Beach just north of Cypress Point overlain with the high-resolution bathymetry by Chase (1993). Most of the perennial streams that used to drain this section of the peninsula have been filled during the construction of golf courses in this area, substantially reducing the input of sediment to the nearshore. The few shore-parallel ribbons of sediment tend to lie leeward of offshore rocks.

Fig. 9. Interpreted sediment distribution along the nearshore and inner shelf between Cypress Point and Stillwater Cove overlain with low-resolution bathymetry by the National Oceanographic and Atmospheric Administration (1998). The absence of shore-normal sediment-filled channels is likely due to the lack of significant drainages along this section of the peninsula. This part of the peninsula is uplifted along the southwest side of the Cypress Point Fault (Clark et al., 1997).


Location
6 = Beach study site
Km
0
1
C.I. = 10m (0-30m)
N
= Land
= Rocky substrate
= Sediment
= Perennial stream
= Terrestrial paleo-stream channel
= Fault (see Figure 2)
Cypress Point
19
30
20
10
U
D
Cypress Point Fault
Pescadero Point
20

5. Discussion

5.1. Nearshore sediment sources, transport pathways, and sinks

5.1.1. Northern Monterey Peninsula: Point Piños to Monterey Harbor

The beach sediment along the northern coastline of the Monterey Peninsula appears to be a combination of: (a) material eroded from porphyritic granodiorite outcrops by wave action or deposited by streams and then transported eastward along the coast by waves and currents; and (b) relict sediment originally from the Salinas River to the north of the study area transported onshore by northwesterly waves or wind during sea level lowstands, as discussed by Combellick and Osborne (1977). The rapid development of the beach to the west of the harbor since the breakwater's emplacement (Fig. 3) indicates eastward transport across the northern part of the peninsula (Fig. 10). The sediment at Point Piños is similar in composition to the Monterey Mass granodiorite porphory (Ross, 1979) that outcrops along this section of shoreline and as the sediment fines to the east, it appears to be increasingly diluted by more quartzitic sediment that resembles the siliceous sediment northeast of the harbor. An offshore source for this sediment is supported by its quartzitic character and similarity to littoral sediment derived from the Salinas River farther to the north (Yancey, 1968; Combellick and Osborne, 1977).

Under high energy or storm conditions, part of the beach sediment typically is eroded and carried offshore. Offshore transport, which may be focused in the bathymetric depressions offshore from pocket beaches, could disperse littoral sediment across the nearshore. Offshore transport onto the inner shelf likely occurs during high energy or storm conditions due to downwelling bottom currents (Niedoroda and Swift, 1981; Field and Roy, 1984; Cacchione et al., 1984; Wright, 1987). Although we lack current and wave data for sites in the study area, we hypothesize that the alongshore transport of sediment is driven by waves and currents during and after the passage of storms based on high-resolution in situ measurements taken in a similar setting approximately 40 km to the north (Jaffe and Storlazzi, 1999; Storlazzi and Jaffe, 1999), as shown schematically in Fig. 11. During a storm, orbital wave motions would entrain sediment that would then be carried offshore by either seaward near-bed flows driven by wave- and wind-induced set-up at the shoreline or intense rip currents, dispersing sediment both in the bathymetric depressions and on the inter-basinal highs offshore of the subaerial headlands as demonstrated in Fig. 11b (Reimnitz et al., 1976; Cowell, 1986; Jaffe and Storlazzi, 1999; Storlazzi and Jaffe, 1999). As wave heights decrease, small, short-period waves obliquely approaching the shoreline could initiate alongshore currents that would sweep the sediment deposited in the nearshore and on the topographic highs alongshore at shallow depths, feeding the downcoast pocket beaches and their adjacent shore-normal subaqueous depressions. Smaller, long-period swells incident from the southwest, which typically occur during the summer months and have been observed in situ to the north (Jaffe and Storlazzi, 1999; Storlazzi and Jaffe, 1999) could then drive the sediment eroded from the beaches and deposited in the paleo-stream channels shoreward (Fig. 11c). This onshore transport of littoral sediment would further aid in the reconstruction of the pocket beaches and the return of the system to a pre-storm configuration (Fig. 11a).

Some of the sediment along the beaches of Monterey may be lost to the littoral system either (a) by bypassing the harbor and being deposited on the wide beaches and in the dunes northwest of the harbor, or (b) recirculated back onto the deeper portions of the shelf. The return of sediment to depth by offshore transport is hypothesized to occur in the sediment-filled subaqueous channels that are oriented roughly shore-normal in shallow depths (Figs. 5 and 6). This is supported by the similarity of the sediment in these channels at depth (3–6 m) with the sediment on the subaerial beaches and the decreasing concentration of shell fragments in bedform troughs with increasing depth observed during scuba dives off Monterey and Pacific Grove. These channels appear to be the offshore extension of many of the small streams that drained the Monterey and Pacific Grove area.

5.1.2. Western Monterey Peninsula: Point Piños to Cypress Point

Farther to the west between Point Piños and Cypress Point, the mineralogic composition of the

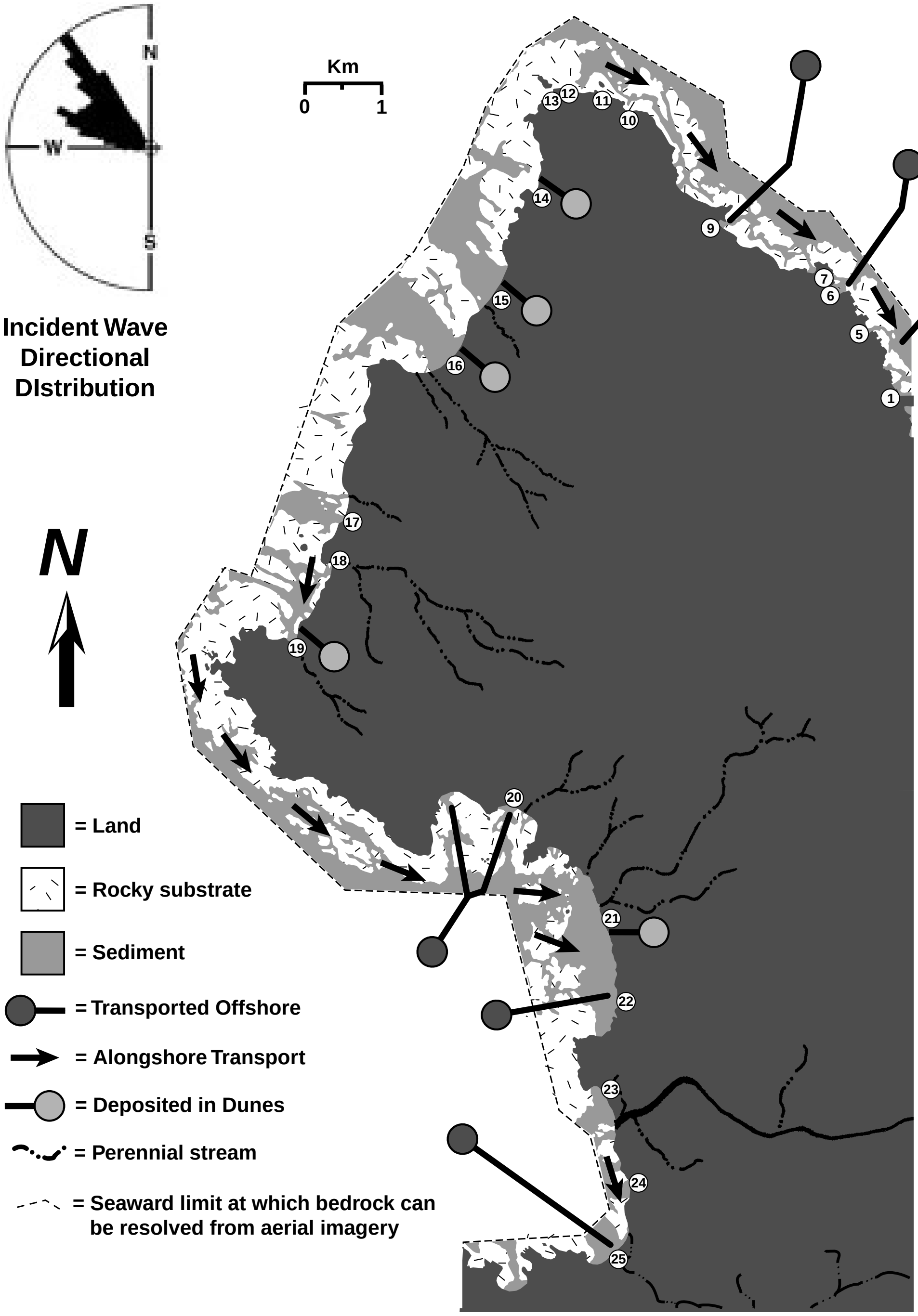
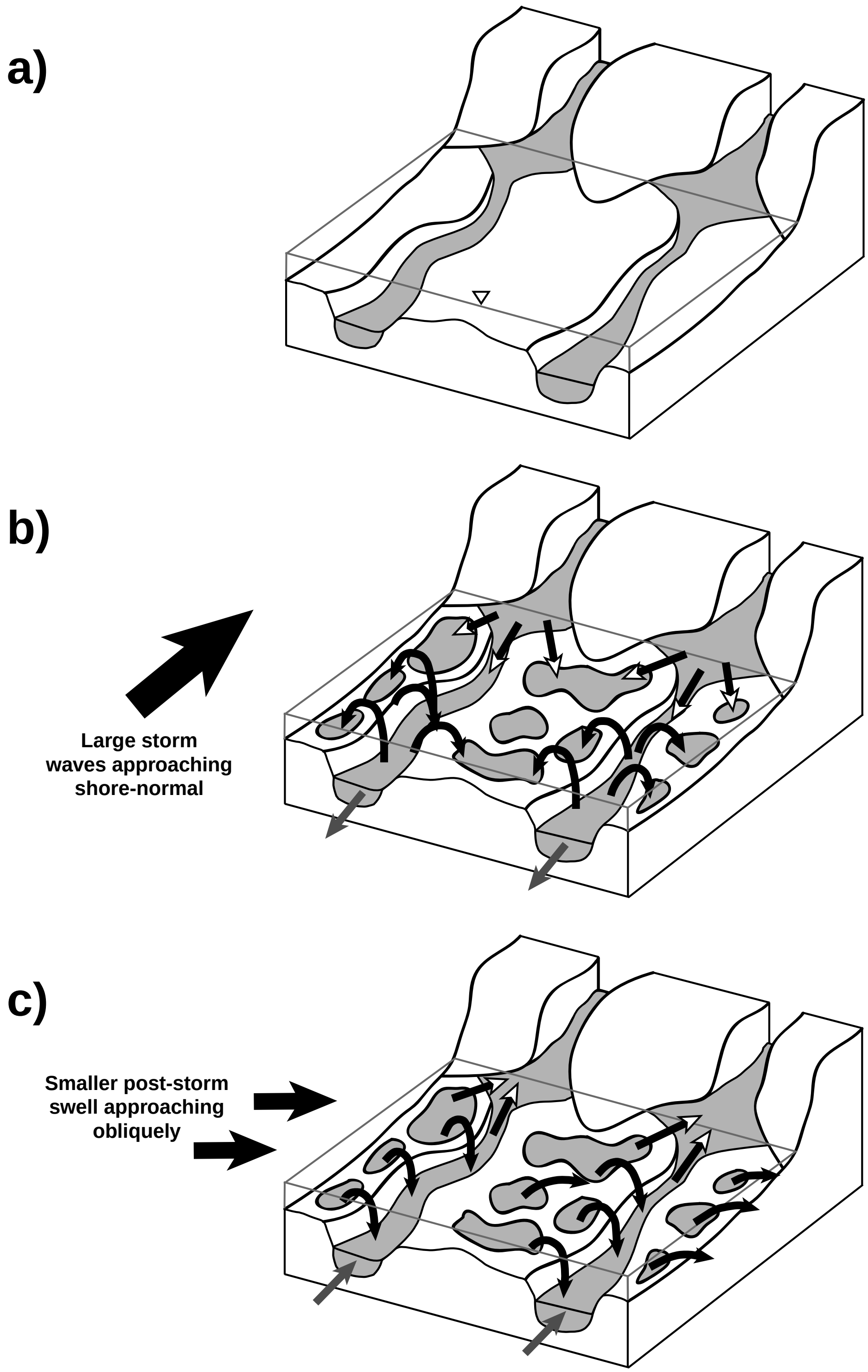


Fig. 10. Interpreted sediment distribution overlain by the dominant littoral sediment transport pathways and sinks along the study area. The wave rose for the central coast was compiled from over 12 000 deep-water buoy observations between 1995 and 1998 (Coastal Data Information Program, 1998). Note the correlation between transport pathways and sediment patterns.


a)
b)
Large storm
waves approaching
shore-normal
c)
Smaller post-storm
swell approaching
obliquely

littoral sediment suggests derivation from subaqueous and subaerial erosion of exposed Monterey Mass granodiorite porphory (Ross, 1979). The presence of a low gradient shoreface offshore of the pocket beaches along this area facilitates onshore transport by wave action by causing most of the incident wave energy to be dissipated by breaking farther offshore and thus reducing nearshore wave heights as observed in the field.

If the dominant northwest wind and swell control onshore deposition, they may play a role in transporting sediment along and on to the pocket beaches, supplying the active dune fields that back Spanish Bay, Seal Rock, and Fan Shell Beach. With the exception of Monastery Beach in southern Carmel Bay, this section of the peninsula typically is exposed to the largest waves encountered along the study area. These greater heights, in conjunction with the numerous headlands, cause waves to refract and break much farther offshore, presumably driving sediment primarily cross-shore. Only in areas protected by offshore rocks, or during the infrequent days when small waves that have short enough periods to propagate into shallow depths at non-normal incident angles, would significant alongshore transport of sediment in the nearshore likely occur. This most likely explains the general scarcity of prominent shore-parallel ribbons of sediment, and where these features are observed, they tend to be located in areas sheltered by offshore rocks or bathymetric highs as shown in Figs. 7 and 8.

5.1.3. Northern Carmel Bay

The source of sediment in Stillwater Cove appears to be both the granodiorite porphyry and the Carmelo Formation that crops out along much of the cove's shoreline. Granodiorite-derived sediment is contributed by both streams that drain the southern part of the peninsula and discharge into Stillwater Cove and the eastward transport of sediment along the southern peninsula's shoreface. The lack of any beaches along the southern part of the peninsula, along with the dominant northwesterly wave direction and shore-parallel patches of sediment observed offshore of the surf zone (Figs. 5 and 9), indicates transport of sediment from the peninsula into the cove. Due to the narrow to non-existent shelf to the north, waves from the northwest refract little until they reach Cypress Point. As these waves propagate eastward toward Stillwater Cove and Carmel, they tend to lose energy due to the increasing refraction and bottom friction caused by the wider shelf to the south of the peninsula (Wiegel, 1964). This causes a wave energy gradient to develop that would generate an alongshore current and transport sediment eastward. In our study area, therefore, where the coastline is oriented parallel to the dominant wave direction and paleo-stream channels do not incise the nearshore and inner shelf, littoral sediment appears to be transported alongshore outside of the low-energy surf zone. This is likely accomplished during energetic wave events in combination with strong northwesterly winds.

Distinct large volcanic pebbles are present in the low bluffs of the Carmelo Formation that back the southern part of Stillwater Cove, and their presence in beach and nearshore deposits verifies that a significant fraction of the littoral sediment originated from these bluffs. Littoral sediment in this area is probably transported offshore and ultimately into the Carmel submarine canyon via nearshore channels identified in the bathymetry and aerial imagery. Arrowhead Point, which is composed of Carmeloite volcanics, is resistant to erosion and appears to be an effective barrier to southward sediment transport out of Stillwater Cove. South of Arrowhead Point, the littoral sediment is interpreted to be dominantly derived from the eastward transport of sand derived from granodiorite on the peninsula. Fluvial deposition

Fig. 11. Schematic diagram showing hypothesized model for alongshore sediment transport along a rocky, embayed coastline. (a) Pre-storm: a subaerial beach between headlands and sediment offshore in a paleo-stream channel bounded by subaqueous bedrock ridges. (b) Storm: subaerial beach sediment is eroded and carried offshore (white-tipped arrows), sediment in the paleochannels is suspended and dispersed across shoreface (black-tipped arrows), and a percentage of sediment in the paleo-stream channels is transported further offshore to the midshelf (gray arrows). (c) Recovery: smaller short-period waves (moving from left to right) would sweep the bedrock ridges clear of sediment, transporting the sediment either onshore to rebuild the pocket beach (white-tipped arrows) or into the adjacent downcoast paleo-stream channel (black-tipped arrows). The reconstruction of the pre-storm shoreface profile would then be aided by long period, low-energy swells carrying sediment onshore from greater depths (gray arrows).

at the northern end of Carmel Beach and erosion of the bluffs behind central and southern Carmel Beach also likely contribute a small fraction to the beach and nearshore, which is reflected in the beach's slightly higher quartz component. The sediment is of distinctly different composition than that to the north in Stillwater Cove, thus excluding southward transport from the northeastern corner of Carmel Bay. The sediment's offshore origin is supported by: (a) the similarity of this sediment to that along the western part of the Monterey Peninsula; (b) the dominant wave direction; (c) the shore-parallel patches of sediment off of the southern part of the peninsula; and (d) the presence of large dunes of similar composition but finer grain sizes behind northern Carmel Beach. Our analysis supports similar conclusions by Habel and Armstrong (1977) and Chin et al. (1993) based on heavy mineral analyses.

The higher percentage of quartz and lower percentage of plagioclase feldspar along the southern end of Carmel Bay appear to be the result of: (a) the granodiorite-derived sediment eroded from the peninsula at the northern end of the beach being increasingly diluted by material contributed by the coastal bluffs; and (b) the weathering of feldspars during transport from the river to the southern end of the bay. Sediment along Carmel Beach may be transported and ultimately lost to the offshore via a small channel that trends landward toward the southern end of Carmel Beach. This is supported by the absence of feldspathic sediment that characterizes Carmel Beach to the south of Carmel Point along Carmel River State Beach.

5.1.4. Southern Carmel Bay

Based on mineralogy and texture, we interpret the littoral sediment along the shoreline to the south of Carmel Point in southern Carmel Bay to be derived from the Carmel River. Carmel River State Beach sand is similar to that in the slough and riverbed and appear to be originally derived from rocks of the siliceous Monterey and Santa Margarita Formations that are exposed along much of the upper reaches of the Carmel River.

The decrease in the percentage of Fe- and Mg-rich minerals toward Monastery Beach is one indicator that beach sediment along the southernmost section of Carmel Bay is discharged from the Carmel River and transported southward by the dominant northwesterly waves and wave-induced currents. Sediment coarsening and the decrease of heavy minerals to the south implies a transition from a depositional regime at the Carmel River mouth to an erosional regime at Monastery Beach where the finer sediment is winnowed-out. This is likely due to the higher wave energies typical at this site due to focusing at the head of the Carmel Canyon. Sediment is lost from the littoral system off Monastery Beach via the deeply incised Carmel Canyon (Dingler and Anima, 1989).

5.2. Long-term changes in beach width: 1949–1990

The beaches along the Monterey Peninsula and Carmel Bay display a general decrease in beach width between 1949 and 1990 (Fig. 3). The northern peninsula beaches appear to have undergone negligible erosion when taking into account the ± 5 m maximum possible error in determining the beach widths at the scale of the 1:20 000 imagery. However, apparent decreases in beach width may be the result of increased development along the northern section of the peninsula over the past century, which has lessened erosion of the granodiorite that is a significant component of these beaches' sediment. This is likely due to the reduction of subaerial drainages due to flood control, the removal of natural drainage channelstion through sewers, and the planting of more robust non-native vegetation that helps to retain the sediment cover, thus reducing bedrock erosion.

Along the western part of the peninsula, however, the significant reductions in beach width observed probably are related not only to the increased development along this section of the coast, but also the sand mining carried out on the dunes backing Spanish Bay that was terminated in the 1970s (Griggs and Savoy, 1985). The construction of numerous golf courses and private homes along this section of the peninsula has also reduced the amount of fluvial sediment reaching the shoreline. The majority of the drainages observed in the 1949 aerial photographs that flowed into Spanish Bay, Moss Beach, Bird Rock, Seal Rock, and Fan Shell Beach have since been infilled or armored, thus retarding local erosion and decreasing the supply of sediment to the beaches. The dunes backing Spanish Bay and Moss beach are thought to be a major short-term source of littoral sediment when eroded during high energy conditions (Combellick and Osborne, 1977), and mining sand from the dunes probably intensified beach erosion along the western coast of the peninsula.

The housing boom during the latter half of the 20th century appears to have caused increased erosion along the northern section of Carmel Bay by reducing the delivery of sediment by the few local streams that back Stillwater Cove and Carmel Beach, similar to that observed along the northern portion of the peninsula. To the south of Carmel Point, the decreases in beach width along Carmel River State Beach and Monastery Beach are also likely due to the recent development in the area. Both the Carmel River and San Jose Creek channels have been stabilized through armoring of the banks and planting of non-native vegetation. Increased soil runoff in the agricultural areas upstream has effectively reduced these waterways' ability to erode bedrock and create sediment for the littoral environment by choking the channels with fine sediment.

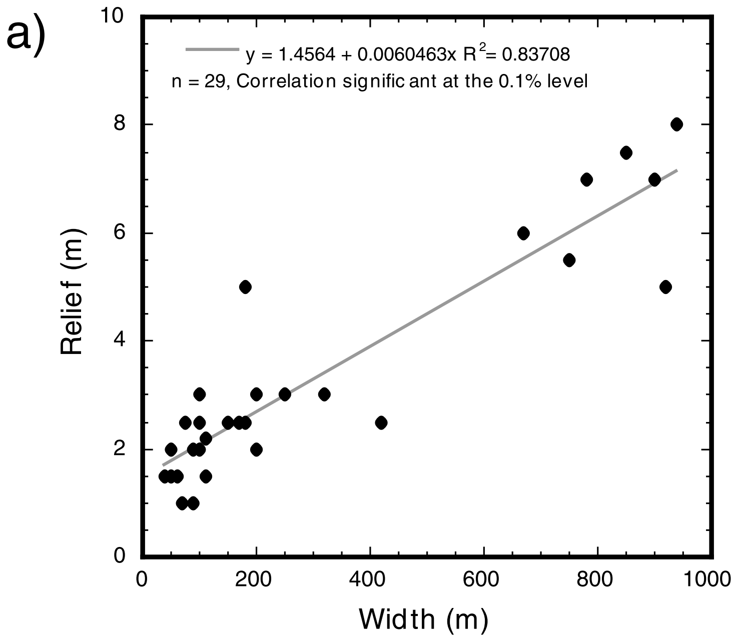
5.3. Implication of results to sediment transport along rocky coastlines

Local geologic structure appears to be one of the principal controls on the distribution of littoral sediment along not only the Monterey Peninsula and Carmel Bay, but other rocky sections of California's coastline as well. Stresses associated with the obliquely converging Pacific Plate with the North American Plate is expressed by the northwesterly trending Palo Colorado–San Gregorio and Monterey Bay Fault Zones that appear to have played an important role in the development of the joint patterns and the resulting morphology in the study area. Subaerial drainages developed along these structural weaknesses and their courses were dictated by the structurally-controlled topography. During periods of lower sea level, these streams flowed across the continental shelf and discharged at or near the shelf edge. At that time, these streams apparently incised the bedrock along the present nearshore and shoreface with a drainage pattern similar to that observed onshore today. As sea level rose, these offshore channels were inundated and filled with sediment derived from: (a) reworking and transport shoreward across the shelf during the transgression; (b) transport alongshore from other sources; or (c) fluvial sources or local seacliff erosion. The combined effect is a general geologic framework that was shaped by local tectonics and further modified by fluvial incision during sea level oscillations. The width and depth of the paleo-stream channels tends to roughly correlate with the size of the streams' drainage area, demonstrating the influence of the streams, and thus the topography and local tectonic regime, on the morphology of the shoreface (Fig. 12).

The dominant oceanographic regime provides a key secondary influence on sediment distribution. Wave and wind approaches determine the primary direction of sediment transport over intermediate time-scales and the bathymetry and shoreline orientation dictate wave refraction patterns, the resulting wave energy gradients, and wave-driven currents. These gradients and currents then define the finer-scale modes and directions of sediment transport as reflected in the beaches' mineralogic and textural properties.

Along our study area, the northwesterly shearing, extension, and tilting of the Santa Lucia block along numerous faults (Greene, 1977; Greene and Clark, 1979; Chin et al., 1993) dictated the northwesterly, southeasterly, and westerly drainages that characterize the topography and bathymetry of the Monterey Peninsula and Carmel Bay. This first-order control imposed by regional tectonics has been observed elsewhere in central and northern California by Cacchione et al. (1984, 1987), Tait et al. (1992), Anima and Tait (1994), and Tait (1995). Here, the translational movement and uplift associated with the SAFS has formed the relatively continuous Coast Range that is oriented roughly parallel to the shoreline. These coastal mountains are drained by a number of steep streams that have incised the nearshore and shoreface, leaving a series of sand-filled, shore-normal channels similar to those observed along our study area, although much larger in scale and in greater water depths. It therefore appears that the interaction between the tectonic regime and fluvial incision during sea level fluctuations has formed the two primary features that control the distribution of littoral sediment along the study area and elsewhere along rocky coasts: (1) headlands fronted by steeply sloping bathymetric highs; and (2) more gently sloping bathymetric depressions extending offshore from pocket beaches or coastal sloughs.

The presence of rocky headlands that extend out



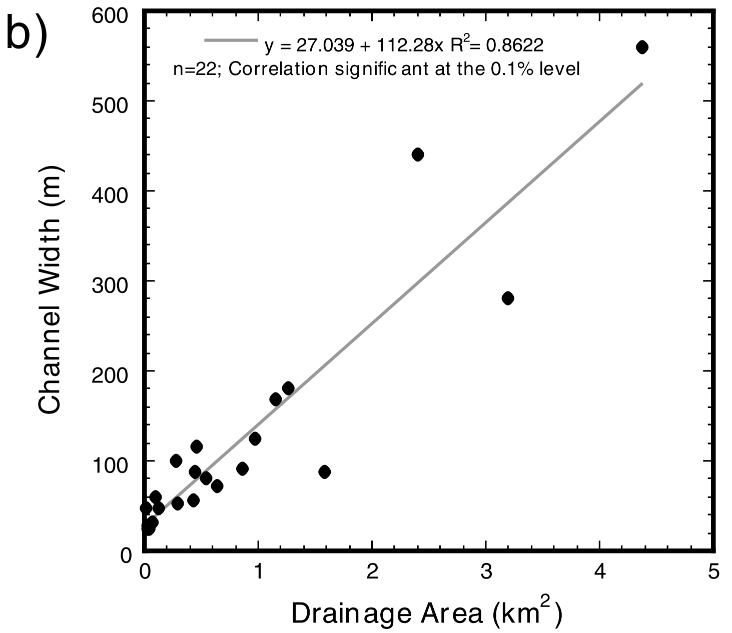


Fig. 12. Plots demonstrating the relationships between: (a) paleo-stream channel width and depth; and (b) drainage area of major streams in the study area, a proxy for stream power, and subaqueous paleo-stream width. These relationships illustrate the influence of the streams draining the peninsula, and thus the topography and tectonic regime, on the morphology of the surfzone and inner shelf along the study area.

into and often past the low-energy surf zone precludes the littoral drift mechanism, which is characterized by the continuous alongshore movement of sediment down the beachface and in the nearshore due to oblique wave approach, for significant longshore sediment transport common to long, sandy coastlines. High-energy events (i.e. storms) therefore appear necessary to move the sediment far enough offshore from the pocket beaches to bypass the adjacent headland and supply the next pocket beach some distance downcoast. The substantial depths at which littoral sediment is observed, in conjunction with the bathymetric relief observed between sediment-filled depressions and inter-basinal bathymetric highs, makes it further apparent that large storm waves are necessary for alongshore sediment transport along rocky coastlines (Cacchione and Drake, 1990; Tait, 1995). The sharp, shore-normal vertical faces of many of these subaquoues bedrock ridges observed during scuba dives precludes the alongshore movement of sediment by bedload transport.

To transport significant volumes of sediment from one pocket beach to another, sediment must first be moved cross-shore, out past the surf zone, to bypass the intervening headland. This likely occurs during the passage of storms from the southwest commonly observed during El Niño-Southern Oscillation events that would generate strong offshore bottom flow near the bed due to set-up caused by wave- and wind-induced onshore transport (Storlazzi and Griggs, 2000). Wright (1987) discusses how these cross-shore exchanges of sediment between the beaches and the shoreface are fundamental to the episodic changes in beach and surf zone sediment storage over intermediate time-scales as well as to longer-term erosional or accretionary trends. Once the sediment has moved far enough offshore to bypass the intervening headland, the sediment then must be advected, from a much greater depth than in the surf zone, to a height sufficient to allow alongshore flows to carry the sediment over the inter-basinal bathymetric highs. This is in contrast to much of the East and Gulf coasts of the United States where alongshore wind-driven and/or tidal currents are the primary forcing factor in the alongshore transport of littoral sediment on the inner shelf (May, 1979; Niedoroda et al., 1985). The distance offshore and water depth that the sediment must attain to bypass headlands, and the heights above the seafloor to which they must be elevated to move over the submerged bedrock ridges, necessitate much higher bed shear stresses than those typically generated by tidal currents (Wright, 1987).

The more energetic oceanographic conditions along central California have been shown to mobilize sediment at depths greater than 30 m (Hunter et al., 1988; Cacchione and Drake, 1990; Seelbach, 1993; Tait, 1995). This is likely due to the combined effects of strong oscillatory wave orbital motions and a steady current. Wave-current interactions generate higher bed shear stresses than if either process acted alone and can pump sediment high into the water column due to high shear not only at the bed, initiating sediment suspension, but also at the top of the combined wave-current boundary layer (Grant and Madsen, 1979; Grant et al., 1984). Therefore, large wave events apparently play distinctly different and perhaps a more critical role in the transport of littoral sediment along rocky, embayed coastlines than along continuous sandy coastlines. Because these energetic conditions are often the result of local storm activity, it seems evident that the frequency and intensity of storms exerts significant control on the timing and magnitude of sediment transport along rocky coastlines.

6. Conclusions

Three primary modes of sediment distribution in the nearshore and on the inner shelf off the Monterey Peninsula and in Carmel Bay were observed. Where the coastline is exposed to the dominant wave direction, sediment is found in shore-normal bathymetric lows interpreted to be paleo-stream channels. Along sections of the coastline that is oriented parallel to the dominant wave direction and streams channels trend perpendicular to the coast, sediment-filled shore-normal paleo-stream channels occur in the nearshore as well, but these features are connected to one another by shore-parallel ribbons of sediment at depths between 2 and 6 m. Where the coastline is oriented parallel to the dominant wave direction and onshore stream channels are not present, however, only shore-parallel patches of sediment at depths greater than 15 m are present.

First-order controls on the distribution and transport of littoral sediments along the rocky, sediment-deficient nearshore and inner shelf off northern and central California are the tectonic regime intrinsic to the region and the oceanographic forcing that acts to modify the patterns imposed by the geologic structure. The shoreline of Monterey Peninsula and Carmel Bay, California, is characterized by rocky headlands that extend offshore as barren, bathymetric highs adjacent to sediment-filled bathymetric depressions that tend to lie offshore of pocket beaches and coastal sloughs. These headlands and bathymetric highs form barriers to the alongshore transport of littoral sediment not common along passive-margin shorelines. Although littoral sediment has been shown to move downcoast along the rocky shoreline of central California (Griggs and Savoy, 1985; Best and Griggs, 1991), headland bypassing and/or transport outside of the surf zone substantially reduces the efficiency and complicates the pathways of transport. This inefficiency and the non-continuous nature of alongshore littoral transport is reflected not only by the wide variation in the morphologic, mineralogic, and textural properties of the pocket beaches, but also by the temporal changes in beach width along our study area. As the supply of sediment to specific pocket beaches has declined, only nearby beaches were observed to narrow significantly. Thus, the ‘communication’ or interaction between pocket beaches appears to be substantially reduced due to the bathymetric highs that typically separate adjacent pocket beaches and their associated offshore depressions from one another.

The importance of storms to sediment transport along our study area and other rocky coastlines appears to be significant. To bypass headlands and transport sediment outside the surf zone, high wave orbital velocities are needed to mobilize sediment at depth and advect it high enough in the water column to be driven over the bedrock ridges by alongshore flows. This is in sharp contrast to the mechanisms and timing of alongshore littoral transport along the nearly continuous sandy shoreface of coastal-plain shelves. In situ observations of near-bed hydrodynamics, sediment fluxes, and bed responses appear necessary to further constrain the finer-scale mechanisms of both beach-shoreface cross-shore coupling and alongshore transport of littoral sediment in this type of environment.

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