DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Reconnaissance high-resolution geophysical survey of the Monterey Bay, California, inner shelf: Implications for sand resources

By

John L. Chin[1] and Steven C. Wolf[1]

Open-File Report 88-410

Prepared in cooperation with the State of California,
Department of Boating and Waterways

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

[1]U.S. Geological Survey, Menlo Park, California

1988

INTRODUCTION

This report presents the results of a reconnaissance high-resolution geophysical survey of the inner continental shelf of Monterey Bay, California. The survey was designed to delineate potential sources of sand on the inner shelf that might be used for artificial beach nourishment to alleviate Monterey Bay public shoreline erosion problems. It describes the nature, thickness, and geometry of unconsolidated sediment within the inner shelf shallow subbottom based on our reconnaissance geophysical surveys and the limited surface sediment data presently available.

Coastal erosion has become an increasingly important problem in the Monterey Bay area as the property losses and shoreline recession experienced in different parts of the bay have become more severe (Griggs and Johnson, 1979, 1983; Griggs and Savoy, 1985). The winter storms of 1981-1983 in particular are mute evidence of the severity of the problem. The State of California, as a partial solution, has proposed that beaches undergoing recession could be artificially nourished using sand mined from the offshore. However, for artificial beach nourishment to be a viable solution, nearby offshore sources must be located. The original intent of the program was first to define possible offshore sites using high-resolution geophysical profiles and surface sediment samples then to quantify and verify these sites with intensive coring surveys. However, due to budget constraints, a detailed coring program could not be undertaken.

STUDY AREA

The study area covered by this investigation encompasses the inner shelf of Monterey Bay from Point Santa Cruz south to Point Pinos (Fig. 1). The western limit falls mainly landward of the 36-m depth contour so as to encompass the shelf area within the commercial dredging limit of about 30-50 m. The eastern limit is the present shoreline. Pertinent geographic landmarks referred to in the text are shown on Figure 1.

PHYSICAL SETTING

Monterey Bay is a crescentic coastal embayment which opens to the west along the central California coast (Fig. 1). Dominant physiographic features within the study area include the Santa Cruz and Monterey Peninsulas, Monterey Canyon, Elkhorn Slough, Salinas River, Pajaro River, Soquel Creek, and San Lorenzo River (Fig. 1). The physical setting will be described in the next two sections.

Offshore

The inner shelf of Monterey Bay (between water depths of about 10 to 36 m) is relatively flat and featureless. However, two different topographic configurations are apparent on bathymetric maps of the area (Fig. 1). The inner shelf isobaths from Point Santa Cruz to the mouth of Elkhorn Slough tend to parallel the shoreline (Fig. 1). At the mouth of Elkhorn Slough, the head of the Monterey Canyon system bisects the shelf to within 0.5 km of the shoreline. South of the mouth of Elkhorn Slough isobaths are deflected seaward off the present mouth of the Salinas River (Fig. 1). This seaward deflection of isobaths creates a prominent bulge in the shelf profile that does not occur on the northern shelf. This bathymetric bulge will be discussed in detail in subsequent sections of this report. The inner shelf between Marina and the Monterey Peninsula, in contrast to that off the Salinas River mouth, is characterized by isobaths that generally parallel the coastline (as on the northern shelf).

Monterey Bay is subject to the individual and combined effects of tides, wind, and waves. Tides in the Monterey Bay area are mixed diurnal and mesotidal in scale. Their range is typically on the order of 2-3 m (Griggs and Hein, 1980). Tides greater than 1.8 m can be expected 25-35 days a year and tides greater than 1.7 m can occur about 100 days a year (Griggs and Johnson, 1983). Tidal currents are usually weak, and the predominant tidal effect along the open coast is the rise and fall of water level.

The prevailing wind regime in the Monterey Bay area is controlled by the semi-permanent eastern arm of the Pacific High (Scott, 1973). Coastal winds alternate seasonally, though, both in direction and intensity. In general, winds blow from the northwest during all seasons of the year. During winter months, though, a weakening of northwest winds occurs and storm winds blow sporadically from the north and south. Strong winds from the south are particularly important in the Monterey Bay area in regard to coastal erosion and property damage.

Most commonly, waves come from the northwest, west-northwest, and southwest (Arnal, 1971; Griggs and Hein, 1980); most waves approach from the northwest. Wave periods typically range from 8-10 seconds, and about 80 percent of the waves arriving in Monterey Bay have wave heights less than 1.5 m (Arnal, 1971). Storm waves occur less that 6 percent of the time and are generally less than 2.1 m high. Griggs and Johnson (1983) point out that even this low frequency of occurrence can have disastrous effects on the coast. They estimate, that over the last 73 years, damaging storm waves from the southwest have impacted the coast of Monterey Bay every 3.6 years on the average. Furthermore, based on wave hindcasting, they state that it is reasonable to expect wave heights greater than 3.0 m to occur on the average of 23 days each year, and waves greater than 4.5 m to occur on the average of 3 days each year. Finally, they suggest that the occurrence of large storm waves during times of high tides is particularly important, and that the probability of such an occurrence is reasonably high.

Onshore

The coastline within the study area differs markedly from the north end at Point Santa Cruz to the south end at Point Pinos (Fig. 1). From Point Santa Cruz to Rio Del Mar, the coastline consists of sandy beaches backed by sea cliffs. These sea cliffs are composed of the Pliocene Purisima Formation (Griggs and Johnson, 1983). From Rio Del Mar south to about the mouth of the Pajaro River (Fig. 1) the coastline is composed of wide sandy beaches backed by sea cliffs composed mainly of the Pleistocene Aromas Sand (Dupre, 1975; Griggs and Johnson, 1983). From the Pajaro River mouth south to the Monterey area the coast is characterized by wide sandy beaches backed by Holocene and

Pleistocene sand dunes. The remainder of the study area coastline, from Monterey to Point Pinos, is characterized by granitic sea cliffs with small pocket beaches. The nature and composition of the coastline, as shown by Griggs and Johnson (1979, 1983) and Griggs and Savoy (1985), is integrally important in the scale and rate of coastal erosion.

Neotectonics have played an important part in the development of both onshore and offshore coastal morphology (Dupre, 1975; Tinsley, 1975; Greene, 1977; Griggs and Johnson, 1979, 1983; Chin and others, in press). The only known faulting believed to occur in the study area occurs along the Monterey Bay fault zone, which trends diagonally across the bay from Monterey northwest to Santa Cruz (Greene, 1977; Greene and others, 1973). However, only the easternmost edge of this fault zone appears to lie within the study area. Greene and others (1973) define the Monterey Bay fault zone as a diffuse zone 10-15 km wide consisting of short en echelon northwest-trending faults. The present sea floor appears to be offset by this fault zone, suggesting that this fault may be active at present.

Several fluvial systems presently debouch into the study area. From Point Santa Cruz going south, they are San Lorenzo River, Soquel Creek, Pajaro River, Elkhorn Slough, and the Salinas River. Sediment is added to the inner shelf primarily during the winter months in response to large, infrequent storms. At present, only the Salinas River contributes a significant volume of sand to the shelf area (Combellick and Osborne, 1977). However, in comparison to northern California streams, the Salinas River's sediment discharge is minor (Griggs and Hein, 1980).

There are several other sediment sources that may contribute sand to the inner shelf. Yancey and Lee (1968), Griggs and Johnson (1979, 1983), Griggs and Savoy (1985), Weber (1981), Hicks (1985), Dingler and others (1985), and Hicks and Inman (1987), among others, suggest that a sizeable volume of sand is introduced into Monterey Bay by littoral drift from the north, possibly from as far north as the San Francisco area. The littoral sand supposedly moves parallel to the northern Monterey Bay shoreline. Ultimately it is thought to be lost by transport down the Monterey Canyon system. Arnal and others (1973) and Combellick and Osborne (1977) suggest that littoral transport across the head of Monterey Canyon is negligible. Thus, the northern and southern Monterey Bay shelves are separated into discrete littoral cells with little to no leakage between them (Dorman, 1968; Arnal and others, 1973). Other potential sand sources are the erosion of coastal cliffs and dunes, erosion of pre-existing shelf sediments, and sand blown offshore from coastal dunes.

METHODS

The sound sources utilized in this investigation to acquire geophysical data all operate on the same basic principle. Seismic energy transmitted through the water column becomes incidental on an acoustic interface and is partially reflected from this interface. The acoustic interface may represent any interface across which there is a contrast in acoustic properties. Contrast is dependent chiefly on the acoustic impedance of the reflecting horizons. This in turn is a function of the density and elastic properties on each side of the interface (Sieck and Self, 1977). The acoustic interfaces are the reflectors displayed on the seismic profiles by graphic recorders. The interfaces may correspond to a variety of physical interfaces in the real world: bedding planes, unconformities, faults, bedrock surfaces, and gas zones among others (Sieck and Self, 1977).

Data used in this investigation were obtained during two separate field studies--each utilizing different shipboard instrumentation and each with different objectives in mind. The south-central Monterey Bay shelf, from the south wall of Monterey Canyon on the west to the shoreline on the east and from Moss Landing to Indian Head Beach at Fort Ord (Fig. 1), was investigated in 1981 as part of a thesis study by the senior author (Chin, 1984; Chin and others, 1986; Chin and others, in press). The objective of this investigation was to characterize externally and internally the thick lobe of sediment off the Salinas River mouth to understand its depositional history.

Navigation for 1981 data was acquired using a Motorola Miniranger III system. Positional accuracy of this navigation system was several tens of meters. Tracklines were plotted by computer from shipboard tapes.

The 1981 survey utilized a EG&G single-plate uniboom system. This system provided single-channel, continuous, seismic reflection profiles of high resolution and shallow penetration along 275 km of trackline (Fig. 2). The incoming signal was filtered between 650-1400 Hz. Other elements of this system included a 10-element hydrophone, pre-amplifier, Krohn-Hite high-low band pass filter, and a EPC 4100 graphic recorder. Minimum visual resolution of profiles is 1.5-2.0 m. Maximum subsurface penetration averaged 50-60 m, while vertical exaggeration averaged 12 times.

The 1985 survey was designed to reconnoiter those areas of the inner shelf not previously surveyed. The objective of the 1985 survey was to provide integrated geophysical data on the nature, geometry, and thickness of unconsolidated sediments in the shallow subsurface that could be used to locate potential sand-mining sites on the inner shelf to nourish adjacent beaches.

Navigation on the 1985 reconnaissance survey utilized a JRC-305 precision range-finding radar unit. Position fixes, using range-range on landmarks and navigation features, were plotted every five minutes. These five-minute fixes correspond approximately to those on the geophysical records. Where possible, position fixes were adjusted using bathymetry. The accuracy of the radar positioning system was estimated at 0.1 nautical mile.

Approximately 350 km of trackline data were obtained on the 1985 survey (Fig. 2). Geophysical data were acquired using an integrated shipboard geophysical system. This instrumentation system consisted of an ORE Geopulse subbottom profiler, Innerspace thermal depth sounder, Klein 500 kHz side-scan sonar and 3.5-kHz subbottom profiler. Geophysical data were recorded in analog format on a Hewlett-Packard Model 3978 eight-channel instrumentation recorder. Side-scan sonar, bathymetery, and 3.5 kHz data were generally recorded on graphic paper only.

All geophysical data obtained on the ORE Geopulse system were single-channel, continuous, seismic reflection profiles acquired at a one-eighth second repetition rate. A band pass filter of 300 Hz to 10 kHz was used in recording geophysical data on the graphic recorders. The geophysical data were displayed every one-eighth second on an EPC 3200 graphic recorder, and the first one-sixteeneth-second segment on an EPC 4800 graphic recorder. Records were automatically marked every five minutes to correspond with navigational fixes.

The ORE Geopulse system was operated at a power output of 105 joules, which provided data between 2 and 14 kHz from depths about one-sixteeneth second below the sea floor (about 45 m of subbottom penetration). Minimum visual resolution on profiles averaged about 0.5 m under optimal profiling conditions.

A Klein 3.5-kHz subbottom profiler was used to acquire high-resolution profiles of the uppermost 5 m of the sea floor. The principal objective of using this system was to provide geophysical resolution within an area of the subbottom that, on one-eighth-second profiles, is often masked by the direct sea-floor arrival. Additionally, unconsolidated sediments tend to be highly "reflective" to the narrow-band 3.5-kHz system as opposed to the broad band of the ORE Geopulse system. This enhanced resolution allowed for a fairly precise determination (in lieu of core data) of unconsolidated sediment. It also provided a means to cross-check minimum thicknesses of sediment derived from ORE profiles. Resolution for 3.5-kHz records was about 0.25 m, while subbottom penetration ranged from 0 to 5 m.

The Klein 500-kHz side-scan sonar system was operated primarily in nearshore areas only. Data were recorded primarily on wet electro-sensitive paper. Occasionally the side-scan data were transposed on the third channel of the EPC 4800 graphic recorder, alongside the ORE and 3.5-kHz data. Most of the side-scan data were recorded using a 50- or 100-m range. The purpose in using the side-scan system was to provide sonographic data that might indicate the presence of bedrock (Fig. 3) or a sandy bottom (Fig. 4), and would thus allow us to verify interpretations made from the other geophysical systems (Belderson and others, 1972).

The Innerspace fathometer, using a hull-mounted transducer, ran continuously at an output of 200 kHz. Its primary purpose was as a cross-check for navigation and to document sea-floor features observed on the other geophysical systems. This shipboard system provided little to no subbottom penetration.

DATA REDUCTION AND INTERPRETATION

Navigation data from the 1981 survey was processed by computer and then plotted by computer at a scale of 1:50,000 on a Mercator projection. Navigation fixes from the 1985 survey were plotted in the field on a nautical chart (NOS, 1981, #18685, 1:50,000 scale, Mercator projection). Tracklines from both surveys were subsequently transferred to a common base map at the same 1:50,000 scale, then photographically reduced for publication.

All geophysical profiles acquired in both the 1981 and 1985 surveys were recorded on magnetic tape. Most of the 1985 survey lines were run under optimal weather conditions, and no post-processing was necessary. Profiles acquired during less-than-ideal conditions were post-processed using a TSS swell-filter. The TSS enhanced seismic data through selective swell removal, stacking, and expansion of the seismic signal.

Water depths on geophysical profiles were derived using a seismic velocity of 1500 m per second and checked against the fathometer records for accuracy. Unconsolidated sediment thicknesses were derived from high resolution profiles using an assumed seismic velocity of 1600 m/s, a figure close to that derived for "Recent" unconsolidated sediments on the Pigeon Point shelf just to the north of the study area (Moore, 1960; Moore and Shumway, 1959).

The major objective in analyzing the high resolution geophysical profiles was to delineate the thickness of unconsolidated sediment in the shallow inner shelf subbottom. The term "unconsolidated" as used in this report refers to shelf sediments that we believe to be loosely aggregated, generally uncemented (non-lithified), and of Quaternary age. However, neither age nor volume of Holocene or Pleistocene sediments could be ascertained since no cores were acquired. Analogs, from a genetic aspect, might be the uplifted onshore Pleistocene terrace deposits, the Aromas Sand, fluvial valley-fill deposits, and the Holocene and Pleistocene coastal dunes. These onshore Holocene and Pleistocene coastal plain deposits are generally unconsolidated. Exceptions may occur due to weathering and diagenetic processes.

Surface sediments of the inner shelf, as shown by previous studies (Galliher, 1932; Monteath, 1965; Dorman, 1968; Yancey, 1968; Wolf, 1970; Scott, 1973; Chin, 1984), are, in general, unconsolidated sands and muds. In most cases these unconsolidated sediments probably extend to some depth below the sea floor. However, since the coring phase of this investigation was not undertaken, we cannot ascertain the quantity or quality of unconsolidated subsurface sediment present on the inner shelf. Chin (1984) reported that at least 1.0 m of unconsolidated sediment exists over most of the south-central shelf. Hunter (1971) found, using a vibracore, that the southern shelf off Fort Ord and Monterey has at least 5-6 m of unconsolidated sand in places. Exceptions occur primarily near peninsular headlands and on the outer shelf where clasts of crystalline rock and lithified sediments have been sampled (Galliher, 1932; Dorman, 1968; Malone, 1970; Yancey, 1968; Scott, 1973; Greene, 1977; Chin, 1984). In conjunction with such existing data we can, therefore, derive a reasonable estimate of the thickness of unconsolidated sediment for the inner shelf.

Examination of onshore outcrops from Point Santa Cruz to Rio Del Mar (Fig. 1) reveals that semi-lithified to lithified Tertiary sedimentary strata comprise the sea cliffs. Previous investigators (Bradley, 1957, 1958; Bradley and Griggs, 1976; Greene, 1977) suggest that these strata extend under the present beach and inner shelf. The modern sea floor may, in places, be composed of a wave-cut platform cut into these Tertiary strata (Bradley and Griggs, 1976). Occurrences of kelp (in growth position) and reworked concretions on the innermost northern shelf support this interpretation.

Thus, we can deduce that parts of the innermost northern shelf (adjacent to Point Santa Cruz and Soquel Cove) consist of "bedrock" (lithified strata) with little to no unconsolidated sediment cover.

Dorman (1968) and Greene (1977) both report the presence of rock outcrops on the shelf surface adjacent to the Monterey Peninsula. Locally, the sea floor is composed of lithified to semi-lithified strata (Tertiary and older in age) with little or no cover of unconsolidated sediment. Greene (1977) found on deep-penetration geophysical profiles that the rocks outcropping at the sea floor extend below the southern shelf of Monterey Bay. Thus, we can also assume that the southernmost part of the study area adjacent to the Monterey Peninsula has little or no unconsolidated cover in places.

The innermost shelf adjacent to Santa Cruz and the Monterey Peninsula were profiled as part of the 1985 reconnaissance survey. Our objective was to establish the acoustic character of these lithified strata for comparison with the unconsolidated strata that are the focus of this report. This allowed us to delineate the attitude and stratigraphic package(s) we would encounter as the bedrock was followed into shelf areas away from the peninsulas.

Our profiles reveal that the lithified to semi-lithified strata are markedly different in acoustic character from the unconsolidated sediments that overlie them (Fig. 5). Where lithified rocks are exposed on the sea floor they may appear on the side-scan sonar record (Fig. 3) as well-bedded and folded strata (Belderson and others, 1972). Their acoustic signature on seismic reflection profiles is characterized by high contrast (dense/dark lines) reflectors that dip at an angle steeper than that of the sea floor and commonly terminate upwards against an angular unconformity at or near the sea floor. This angular unconformity is typically one to several cycles thick, of high acoustic contrast, and planar to irregular (suggesting differential erosion). Reflector packages in the unconsolidated strata above the unconformity are markedly different from those in the lithified strata below it. Strata above the unconformity typically are transparent to weakly parallel-bedded with reflectors usually parallel to the dip of the sea floor (Fig. 5). Strata occurring above the unconformity appear to be undeformed. In contrast, strata below the unconformity typically are well-bedded, dip more steeply than the sea floor, and may exhibit an apparent dip that is opposite in sense (direction) to that of the sea floor. Strata that occur below the unconformity are commonly deformed (folded and faulted) (Fig. 5).

In general, we traced the acoustic horizon representing the top of the lithified section (often represented by an angular unconformity) from nearshore areas where we were certain of its signature into deeper shelf areas. This method provided us with reference depths to ascertain the thickness of unconsolidated sediment above lithified strata. Using this method, we also were able to cross-check our data by comparing depths at the crossing points of tracklines. Where the lithified horizon could not be traced into the subsurface, as off the Salinas River mouth, we used the marked difference in acoustic signature across a shelf-wide angular unconformity to delineate the respective strata.

RESULTS

Northern Shelf Survey

The shelf area discussed in this section runs from Point Santa Cruz to Elkhorn Slough (Fig. 1). The area is bounded on the north and east by the coastline, on the south by the north wall of Monterey Canyon, and on the west by the 36-m-depth contour.

The isopach map constructed from seismic reflection profiles (Fig. 6) shows several trends in the distribution of unconsolidated sediment across the northern shelf. Due in part to the curvature of the coast, the northern shelf area in water depths less than 36 m is larger than that of the southern shelf. However, much of the northern shelf is covered by less than about 6 m of unconsolidated sediment. Moreover, in water depths less than about 18 m, the shelf is characterized by an unconsolidated veneer 0-1 m thick. This thin veneer thickens locally off the Pajaro River mouth, then thins again approaching the mouth of Elkhorn Slough (Fig. 6).

The innermost shelf from Santa Cruz to the cement ship near Rio Del Mar (Fig. 6) is an area with little or no unconsolidated sediment. We mapped an upper limit of 0.5 m due to the theoretical resolution of our profiling systems. Our 0- to 0.5-m contour correlates well with the position of kelp plotted on NOS sheet 18685 (1981). Fischer and others (1983) state that the seaward limit of kelp closely correlates with the zero sediment edge, which supports our interpretation. A representative profile (Fig. 7) reveals folded strata which rise toward the sea floor and are truncated at or near the sea floor by an unconformity. In places, where the folded strata are apparently truncated at the sea floor, the erosional surface may be coincident with the Holocene wave-cut platform reported by Bradley and Griggs (1976). The angular unconformity observed on seismic profiles at or near the sea floor is similar to that observed in the sea cliffs where an uplifted Pleistocene marine terrace truncates the underlying Tertiary Purisima Formation (Griggs and Johnson, 1979).

The isopach map (Fig. 6) shows a general thickening of unconsolidated sediment from the shoreline seaward to the outer limit of the study area. The shelf north of a west-trending line from the Pajaro River mouth is characterized by only about 6 m of sediment in water depths less than about 36 m. Moreover, the greater part of the northern shelf is characterized by only 1-3 m of unconsolidated sediment (Fig. 6).

West-southwest of the Pajaro River mouth, the sediment cover changes from a thin tabular veneer to a westward-thickening lens that attains a maximum thickness of 12 m, centered around a water depth of 18 m. Figure 8 shows that this lens is bedded with all reflectors parallel to the sea floor. The sediment lens overlies an angular unconformity that dips to the west and rises to within a few meters of the sea floor just off the river mouth. The subsurface structure is complex because several additional unconformities appear below the uppermost unconformity. These lower unconformities rise toward the present coast (east) and are truncated near the sea floor by the uppermost unconformity. The lower unconformities exhibit high acoustic impedance contrasts, suggesting they may occur within semi-lithified to lithified strata.

Another facet of sediment distribution across the northern shelf, which is shown on the isopach map (Fig. 6), is the apparent structural control on sediment geometry. Although the general trend is a westward thickening of sediment from nearshore to offshore, an exception occurs adjacent to the head of Soquel Canyon and west of the Pajaro River mouth in water depths greater than 36 m where the sediment cover thins significantly and appears to be locally absent.

A topographic high in the subsurface appears to separate two distinct depocenters. As Figure 6 shows, the northern depocenter occurs adjacent to the head of Soquel Canyon while the southern depocenter occurs just southwest of the Pajaro River mouth. The northern site is largely seaward of the commercial dredging limit, its thickest area (10 m) is centered near 73 m of water depth. It is not clear, based on our trackline coverage, whether this depocenter thickens outside of the study area between the 37- and 55-m isobaths.

The southern depocenter is more clearly delineated and is centered around the 36-m isobath off the river mouth. It reaches a maximum thickness of 12 m in about 36-m water depth. This depocenter is asymmetric, its thickest point is directly off the river mouth and it thins in all directions away from this locus (Fig. 6). The asymmetric orientation and skewing toward the topographic high suggest that pre-existing shelf topography and/or neotectonics influenced sediment accumulation on this part of the shelf in a manner similar to sediment accumulation on the shelf off Santa Cruz (Mullins and others, 1985).

In water depths greater than 36 m, the shelf appears to have a sedimentation pattern markedly different from that of the inner shelf. Although trackline coverage is sparse, it appears that sediment thickness increases across the outer shelf in the area between Point Santa Cruz and the head of Soquel Canyon (Fig. 6). The outer shelf east and southeast of the Soquel Canyon head is characterized by a thin to locally-absent sediment cover (Fig. 6). The aforementioned topographic high is but one feature where semi-lithified to lithified strata occur at or very near the sea floor. The outer shelf between Soquel Canyon and the unnamed double-headed canyon off the Pajaro River mouth and southwest of the topographic high has, in general, less than 3 m of sediment and may be devoid of unconsolidated sediment locally. Geophysical profiles over the outer shelf reveal a thin (to absent) veneer of unconsolidated sediment that overlies an angular unconformity. This unconformity truncates high-acoustic amplitude strata that dip at an angle greater than that of the sea floor.

The southernmost part of the northern shelf, west of Zmudowski State Beach and northeast of the north wall of Monterey Canyon, is a stratigraphically complex area. Using criteria derived from areas where unconsolidated strata can be confidently delineated from lithified strata, we interpret this area to be covered by only a thin veneer of unconsolidated sediment. This thin veneer overlies strata with an acoustic character similar to the previously mentioned criteria for semi-lithified to lithified strata. These "older" strata are well-bedded, of moderate to high acoustic impedance, and exhibit multiple unconformities. Their relationship to "older" strata to the north is not clear except that they are probably not crystalline bedrock.

SOUTH-CENTRAL SHELF GEOPHYSICAL SURVEY

The shelf area discussed in this section is bounded by Monterey Canyon on the north, the coastline as far south as Marina on the east, and the 36-m-depth contour on the west. Isobaths west of the Salinas River mouth are deflected seaward in water depths of about 10 to 80 m water depth (Fig. 1). This pattern is in marked contrast to that of the inner shelf of northern and southernmost Monterey Bay where isobaths in general parallel the shoreline (Fig. 1). The south-central shelf also differs from the northern shelf in that no major canyon head(s) cuts the shelf. There is, however, a small re-entrant in the south wall of the canyon that lines up with the present mouth of the Salinas River (Fig. 1). The re-entrant is a topographic depression that varies in width from 0.2 to 0.5 km and is approximately 1.5 km long; it occurs only in water depths of 37 to 130 m. The presence, mode of formation, and genetic relationship of this re-entrant are, at present, controversial (Dorman, 1968; Yancey, 1968; Chin, 1984).

The south-central inner shelf is also narrower than that of the northern inner shelf for water depths less than 30-36 m (Fig. 1). On the south-central shelf, the 36-m isobath is located about 3.3 km from the shoreline. In contrast, that contour is as far as 7 km from the shoreline in the north.

Unconsolidated sediment thickness on the south-central inner shelf was determined by Chin (1984) in an earlier investigation of this part of the bay using several of the same criteria developed in this investigation. There are no known outcrops of semi-lithified to lithified strata within this part of the bay, thus indirect methods had to be employed. Greene (1977) established from dredging on the south wall of Monterey Canyon and over the outer shelf that semi-lithified to lithified Pliocene Purisima Formation sedimentary rocks crop out on the canyon wall as well as at or near the outer-shelf sea floor. Hence, we assumed that these strata occur in the subsurface below the south-central shelf--at shallow depths near the canyon/outer shelf, and at some deeper depth below the inner shelf and coastal plain. Additionally, Malone (1970), Scott (1973), and Chin (1984) recovered semi-lithified to lithified rocks on the outer shelf seafloor surface, suggesting that these rocks crop out there or were reworked from adjacent outcrops. Fossils recovered from surface grab samples (in which these rocks were included) yield a late Pleistocene age (Powell and Chin, 1984). Short gravity cores taken by Chin (1984) indicate that only 1 m or less of unconsolidated sediment may be present in water depths greater than 90-100 m.

Geophysical profiles reveal a relatively thick (up to 34 m) lens of sediment that overlies a high-acoustic amplitude angular unconformity (Fig. 9). This unconformity truncates high-acoustic amplitude reflectors below it which dip more steeply than the sea floor. The lens of sediment coincides with and is the cause of the seaward deflection of isobaths off the river mouth (Chin, 1984). Maximum thickness of the lens occurs adjacent to the 36-m isobath, similar to the lens off the Pajaro River mouth on the northern shelf. The uppermost sediment in the thickest part of the Salinas River lens is thus within commercial dredging limits.

Analysis of high-resolution geophysical profiles reveals that the south-central inner shelf subbottom is grossly similar to that of the northern shelf in that both can be characterized by an unconsolidated sediment layer of variable thickness that overlies deformed strata with angular unconformity. However, the similarity is limited to the gross external seismic configuration. Externally, two different seismic configurations characterize the south-central shelf. Adjacent to the shoreline near Marina-Fort Ord and to the canyon edge (south wall of Monterey Canyon), the shelf is characterized by a thin tabular sheet that overlies an angular unconformity. The tabular sheet rarely attains a thickness in excess of about 8 m. The area off the Salinas River mouth, in contrast, can be characterized by a plano-convex lens that overlies the same angular unconformity seen in adjacent shelf areas. The lens is thickest between the 18- and 36-m isobaths and thins in all directions away from this area.

Internally, all strata above the angular unconformity appear to be undeformed. Reflectors, both within the tabular sheet and within the lens, are poorly to well-bedded (parallel) with the dip of reflectors being parallel to subparallel to that of the sea floor (Fig. 9). Amplitude and continuity of reflectors is low to moderate with transparent zones occurring.

In contrast to acoustic strata above the angular unconformity, acoustic strata below the unconformity typically are of high amplitude (Fig. 9). The marked dissimilarity in acoustic amplitude and the angular relationship of reflectors to the unconformity facilitated delineation of unconsolidated from semi-lithified to lithified strata. We interpret all strata above the angular unconformity as unconsolidated sediments of Quaternary age and the strata below as semi-lithified to lithified sedimentary deposits of early to mid-Quaternary and Tertiary age. Neither drilling nor radiometric age data were available to confirm these ages or lithologies.

All strata occurring above the angular unconformity are shown on an isopach map of unconsolidated sediment (Fig. 6). A contour interval (C.I.) of 4 m was used for southern Monterey Bay due to the greater thickness of sediment, as opposed to that of the northern shelf (C.I. = 1 m).

The thickest area of sediment occurs just west of the Salinas River mouth (Fig. 6). When compared with bathymetry (Fig. 1) it is evident in plan view that the thickest area of unconsolidated sediment is manifest by the seaward deflection of bathymetric contours off the Salinas River mouth. Figure 6 reveals that sediment thickness decreases in all directions away from a depocenter about 3 km west of the river mouth. As a result of this thinning pattern, shelf areas in water depths greater than 90 m and off the Marina-Fort Ord coastline are characterized by only a thin, tabular veneer of unconsolidated sediment that overlies the angular unconformity.

The thickest part of the lens also coincjdes with the approximate location of a change-in-slope of the underlying surface of the angular unconformity (Fig. 10). The change-in-slope separates the steeper nearshore segment (water depth less than 40 m) from the flatter offshore segment (water depth greater than 60 m). This subsurface pattern is similar to that reported by Moore and Shumway (1959) for the shelf off Pigeon Point and also similar to that reported by Mullins and others (1985) for the shelf between Santa Cruz and Davenport. Mullins and others (1985) suggest that the erosional surface and the unconsolidated sediment above it represent a buried marine terrace of Quaternary age.

Comparison of the isopach map (Fig. 6) and the structure contour map (Fig. 10) suggests some degree of structural control on late Quaternary shelf sedimentation and preservation in south-central Monterey Bay. The depocenter does not occur immediately adjacent to the river mouth, but rather it occurs 3 km west on the inner shelf, suggesting that pre-existing topography (and neotectonics) influenced the accumulation of unconsolidated sediment. Mullins and others (1985) also suggest that neotectonics strongly influenced both shelf sedimentation and preservation of unconsolidated sediment on the Santa Cruz-Davenport shelf.

Previous investigators noted the presence of a small canyon re-entrant which cuts the shelf near Moss Landing (Fig. 1) but drew different conclusions as to its age, origin, and genetic relationship (Dorman, 1968; Yancey, 1968). Seismic reflection profiling by Chin (1984) over this feature documents its existence and shows that it extends even further landward than shown on navigation charts of the area. It is last detected on seismic profiles as a 2-m depression in the shelf surface about 2.5 km from the present river mouth. At its distal end, in a water depth of 130 m, it cuts through shelf sediments (the Salinas River delta) to the topographic elevation of the angular unconformity. No buried channel, which would connect the re-entrant to the onshore paleo-valley, could be detected in the subsurface. It is possible, however, that one exists outside of the survey area (Fig. 2) or that the orientation of the profiles did not allow for recognition. Hence, no unequivocal relationship could be established between the re-entrant and onshore paleodrainage. It is clear, however, that this submarine feature may serve as an active conduit of sediments from the shallow shelf into the canyon, resulting in their permanent loss from the littoral system.

SOUTHERNMOST SHELF GEOPHYSICAL SURVEY

The area covered in this section includes the inner shelf from Marina to Point Pinos (Fig. 1). We chose to separate this area from the south-central shelf due to the noticeable change in sediment thickness and bathymetry; it is broadly similar in these aspects to the northern shelf. Figure 1 reveals that the bathymetric configuration of the shelf differs from that off the Salinas River mouth. The shelf just northwest of Marina is characterized by isobaths that diverge as the sea-floor bathymetry is deflected seaward by the increased sediment thickness off the Salinas River mouth (Fig. 1). South of Marina, isobaths straighten out and tend to parallel the coastline. This trend is partly a function of the significant decrease in sediment thickness over the angular unconformity. Also, the inner shelf (less than 30-36 m water depth) is narrower than that in the two previously described areas. The 36-m isobath occurs approximately 1.8 km off the Fort Ord coast and only 1.3 km or less adjacent to the Monterey Peninsula (Fig. 1).

The isopach map reveals three general trends in the distribution of unconsolidated sediment (Fig. 6). From Marina to about the Sand City area, a thin veneer of 4 m or less covers the inner shelf. From Sand City to about Lover's Point, the inner shelf ("Monterey Bight") is practically devoid of unconsolidated sediment with thicknesses in the minimal 0- to 0.5-m range. In this location, semi-lithified to lithified strata outcrop on the sea floor, with or without a thin cover of sand present (Dorman, 1968; Greene, 1977). A third pattern characteristic of the southernmost shelf is the occurrence of a small mound of sediment just northeast of the Monterey Peninsula from Lover's Point to Point Pinos (Fig. 6). Available trackline coverage at this time is insufficient to adequately define its areal extent.

Externally, the seismic stratigraphic pattern for this shelf is characterized by a thin tabular sheet that overlies an angular unconformity (or disconformity). The sheet is characterized by low-amplitude, low-continuity reflectors that parallel the dip of the sea floor. In general, the sheet is 8 m or less thick. The small mound off the Monterey Peninsula appears as a southeastward-thinning lens in seismic profiles.

The angular unconformity underlying the unconsolidated veneer in southernmost Monterey Bay appears similar in form and pattern to that underlying the adjacent south-central shelf as well as that under the northern shelf. As Greene (1977) pointed out, different stratigraphic units (packages) probably underlie the Monterey Bay shelf both in a north-south as well as an east-west sense. A further complicating factor is that the shelf has experienced multiple fluctuations in eustatic sea level, and neotectonics have probably varied across the study area both in style and rate. As a result, we cannot verify whether the angular unconformity (uppermost in the subbottom) is the same unconformity across the study area, or whether it is the same or equivalent age from north to south or from east to west. Based on available evidence though, it does appear fairly certain that sediments occurring above the angular unconformity are unconsolidated in nature.

Although the stratigraphic section below the angular unconformity is complex in southernmost Monterey Bay, the seismic stratigraphic pattern is basically the same as for the rest of the study area. That is, an unconsolidated veneer overlying an angular unconformity of high-acoustic amplitude (and continuity) that truncates steeply-dipping reflectors below it. Reflectors below the unconformity are commonly of high-acoustic amplitude and continuity and are either deformed into structural folds, faulted, or both. Alternatively, the strata below the unconformity may appear as high-amplitude hyperbolae. As with the northern shelf, multiple unconformities may be present in the section below the uppermost angular unconformity. The contrast in acoustic impedance and degree of deformation across the uppermost unconformity once again facilitated our mapping of unconsolidated sediments.

The thin tabular sheet that characterizes the inner shelf from Marina to Sand City thins considerably or is locally missing in the Monterey Bight (Fig. 6). As the sediment veneer thins, the acoustic strata underlying the angular unconformity rise nearer to the sea floor and locally crop out (Fig. 6).

Side-scan sonar run with the seismic-profiling systems verified the existence of semi-lithified to lithified strata cropping out on the sea floor (Fig. 3; Belderson and others, 1972). In summary, much of the inner shelf from Sand City to Point Pinos is covered by only a thin (4 m or less) to locally-absent (0-0.5 m) veneer of unconsolidated sediment. An exception is the mound of sediment off the Monterey Peninsula which extends into water depths approaching 55 m (Figs. 6, 11). The mound reaches a maximum thickness of 14 m in about 39 m water depth. Internally, all reflectors are parallel to subparallel to the sea floor and appear undeformed. The mound overlies an angular unconformity or disconformity.

SUMMARY OF RECONNAISSANCE GEOPHYSICAL SURVEY

High-resolution seismic-reflection profiling reveals that the inner shelf of Monterey Bay is covered by a variable thickness of unconsolidated sediment. The thickness of the unconsolidated section is of primary concern since thicker deposits allow for more efficient excavation in sand mining operations (Hobbs and others, 1985). Shelf areas with the thickest depocenters that are also proximal to shore occur (from north to south) off the Pajaro River mouth, off the Salinas River mouth, and off the Monterey Peninsula (Fig. 6). Whether these depocenters are viable borrow sites for sand mining cannot be established without extensively coring them.

The suitability of these locations as potential borrow sites is dependent on a number of factors including size distribution, composition, and economics of recovery and placement (Meisburger, 1972). The most suitable borrow sand is one that approximates the size characteristics of the native beach material and is composed of particles of hard inorganic material (Meisburger, 1972). A further concern is that the overburden of fine-grained sediment be less than 1 m (Hobbs and others, 1985).

The results presented in this report are from the initial reconnaissance phase of a proposed multiphase/multiyear integrated investigation. We cannot unequivocally delineate specific borrow sites nor determine their quantity or quality of mineable sand without extensive lithologic data to supplement our geophysical data. In lieu of obtaining subsurface lithologic data, we will present a brief description of the grain size of beaches and a brief comparison of surface sediment grain size occurring over the thickest depocenters. The comparison of surface sediments with the shallow subsurface is tenuous at best as mean grain size may vary significantly with depth in the subsurface (Evans and others, 1982). The intent of the comparison is solely to suggest areas, based on thickness and proximity to shore, that might bear further consideration and intensive study in the future.

GRAIN-SIZE CHARACTERISTICS OF MONTEREY BAY BEACHES

The median grain size of Monterey Bay beaches varies widely from Point Santa Cruz in the north to Point Pinos in the south. Sayles (1966) and Yancey (1968) show that the beaches from Point Santa Cruz to Elkhorn Slough are dominated by sand in the medium sand class; from the mouth of Elkhorn Slough to the mouth of the Salinas River, median grain size ranges from coarse sand (north) to medium sand (south). At the mouth of the Salinas River, Sayles

(1966) reports very coarse sand on the beach. From the south side of the Salinas River mouth to Marina, median grain size falls in the coarse sand class. Beaches from Marina to Point Pinos are highly variable, but in general, median grain sizes are in the medium or coarse sand classes (Sayles, 1966).

Meisburger (1972) suggests that an offshore borrow site should contain sand with nearly the size characteristics of the native beach material to be artificially nourished. It is evident from the foregoing discussion on median grain size of Monterey Bay beaches that an inner shelf borrow site would have to be dominated by sand in the medium to coarse sand classes to be of use for artificial nourishment in the Monterey Bay area.

GRAIN-SIZE CHARACTERISTICS OF THE MONTEREY BAY INNER SHELF

Surface sediment distribution trends cited in this section are synthesized from the following: Galliher (1932), Dorman (1968), Yancey (1968), Wolf (1970), Chin (1984), and Dingler and others (1985).The general trend for the Monterey Bay shelf is for median grain size to decrease in a seaward direction from the surf zone to about 100 m water depth. At approximately 100-m water depth Galliher (1932), Yancey (1968), Malone (1970), and Chin (1984) report that a reversal in the seaward-fining trend of surface sediments occurs, and the outermost shelf appears to be covered by a veneer of relict sediments in the coarse sand to gravel size range.

Dorman's (1968) study of southern Monterey Bay suggests that the general seaward-fining trend is interrupted by localized patches of coarser sediment as well as the occurrence of rock outcrops, particularly in the Monterey Bight.

POTENTIAL SITES

Northern Shelf

A potential borrow site based solely on our reconnaissance geophysical survey is situated just west of the Pajaro River mouth (Fig. 6). Maximum thickness of unconsolidated sediment in water depths less than 30-36 m is 12 m, centered on the 36-m isobath. The deposit extends northwest to about Sunset Beach and southeast to about Zmudowski State Beach, and thins in all directions away from the thickest point.

Median grain size of surface sediments over this depocenter ranges from fine to very fine sand (Galliher, 1932; Yancey, 1968; Wolf, 1970). Yancey (1968) furthermore reports a band of medium to coarse sand in the nearshore adjacent to the river mouth. This band would coincide with a sediment thickness of 4 m. The relatively well-bedded nature of the lens in seismic reflection profiles (Fig. 8) suggests alternating lithologies (and/or facies) are present in the shallow subbottom that are sufficient to generate acoustic impedance contrasts. Whether a change to coarser sediment at depth, as opposed to the fine to very fine surface sediments, is responsible for generating the impedance contrasts cannot be evaluated without core data. If surface sediments are typical of sediments in the shallow subsurface the deposit may be too fine-grained for artificial beach nourishment purposes. Furthermore, if the surface sediment is 1 m or greater in thickness the fine-grained overburden may be too great for current sand mining capabilities.

South-central Shelf

Perhaps the most promising borrow site based on our reconnaissance survey is the delta off the mouth of the Salinas River (Figs. 6, 9). The isopach map (Fig. 6) shows that in plan view the delta is asymmetric with its thickest part between water depths of 20 to 36 m about 2.5 to 3 km off the river mouth. The sediment body in cross section is manifest as a lens that overlies a shelf-wide angular unconformity. The lens is thickest in water depths from 13-27 m and thins both landward and seaward.

Comparing sediment thickness with the median grain size of surface sediments reveals that the thickest part of the delta is covered by fine to very fine sand (Chin, 1984). If this trend is representative of sediments in the shallow subsurface or if the surface sediments are greater than 1 m in thickness, the deposit may be too fine-grained for artificial beach nourishment. Chin and others (1986; in press) have shown, however, that the internal stratigraphy of the delta is complex. The lens is relatively well-bedded in seismic reflection profiles suggesting that the changes in lithologies and facies necessary to generate acoustic impedance contrasts are present. The thickness of the deposit (34 m), its proximity to shore (2.5 km), and its location in shallow water depths (13-27 m) make this site a viable prospect for further study.

Southernmost Shelf

The reconnaissance seismic reflection survey revealed several prospective borrow sites in this area. However, only the location off the Monterey Peninsula will be discussed in depth for reasons listed below.

Dorman's (1968) map of surface sediment distribution for this area shows a mushroom-shaped patch of medium to coarse sand just offshore of the Sand City to Fort Ord coast. This patch appears to have its maximum areal extent in water depths from about 18 to 37 m. Our reconnaissance survey shows that sediment thickness over this part of the inner shelf is in general less than 4 m (Fig. 6). Thus the site may be coarse enough but is thin. Additionally, it is possible that at least a portion of this patch is already being mined for commercial sand. Combellick and Osborne (Fig. 1, 1977) show that the Monterey Sand Company and the Lone Star Industries Prattco plant are both located directly onshore of this patch. Both of these sand mining operations presently utilize dragline scrapers that remove sand from the surf zone (Combellick and Osborne, 1977).

A number of investigators (Combellick and Osborne, 1977; Porter and others, 1979; Clark and Osborne, 1982; Griggs and Savoy, 1985) have questioned whether shoreline erosion is occurring in southern Monterey Bay and if the sand dredging operations in the Marina and Sand City areas affect coastal erosion. Since these questions are as yet unresolved they would surely bear consideration as to whether this patch is a viable site.

Reconnaissance profiling revealed a sediment body on the inner shelf adjacent to the Lover's Point to Point Pinos section of the Monterey Peninsula (Fig. 6). Our reconnaissance survey was insufficient to fully map the areal distribution of this sediment body. Within commercial dredging limits of 30-36 m, the mound reaches a maximum thickness of 12 m.

Surface sediment distribution maps present divergent views on the nature of the sediment cover. Dorman (1968) depicts surface sediment as ranging from fine to medium-coarse sand. His map further suggests that this sediment distribution trend continues around Point Pinos and out of the bay. Monteath (1965) shows a band of medium to coarse sand in the approximate area of this sand body. Welday and Williams (1975) show a band of fine to medium sand as well as a coarse sand patch in the area of this sand body. It thus appears that some or all of the sand body is covered by fine to coarse sand. The proximity to shore and thickness of this site suggest it bears further study as to its viability.

SUMMARY

The inner shelf of Monterey Bay, from about 10 m to 36 m average water depth, was investigated through the use of approximately 625 km of high-resolution geophysical trackline data.

The unconsolidated sediments which cover the inner shelf are the product of a complex interplay of factors which have acted throughout the Quaternary. Chief among these are neotectonics, availability of sediment source(s), eustatic sea-level fluctuations, and the presence of the Monterey Canyon system. The resulting inner shelf unconsolidated sediment cover is stratigraphically complex and varies greatly in thickness.

A large portion of the study area on the inner shelf is covered by only a thin tabular veneer ranging from 0-0.5 m to an average of 4 m or less (Fig. 6). The thickest depocenters identified by seismic-reflection profiling occur off the Pajaro River mouth (12 m), off the Salinas River mouth (34 m), and off the Monterey Peninsula (12 m).

A comparison of the three depocenters with surface sediments indicates that the Pajaro and Salinas River deltas may be too fine-grained to serve as offshore borrow sites. This deduction assumes that the surface sediments are typical of sediments within the shallow subsurface and/or that the surface sediment cover is 1 m or greater in thickness. Neither assumption can be verified without intensive vibracoring. The depocenter off Monterey Peninsula appears to be covered by fine to coarse sand and thus may be a viable prospect. However, this site also would need to be verified with intensive vibracoring. Additionally, the deposits lie in water depths which approach the maximum feasible working depths of current sand mining techniques.

Available data on the grain size of Monterey Bay beaches suggest that most beaches in the area would require medium or coarser sand (minimum of 2.0 phi) for artificial nourishment. Hence, all but the offshore Monterey Peninsula site may be too fine-grained for artificial beach nourishment of Monterey Bay beaches.

It must be emphasized that sediments may vary greatly with depth in the subsurface as pointed out by Evans and others (1982). The only way to adequately determine the quantity and quality of sand available within the shallow subsurface is to conduct an intensive vibracoring program and integrate the results with the reconnaissance geophysical survey. This would yield at least a first-order understanding of prospective sites which subsequent coring and geophysical profiling on a site specific basis could quantify.

Recommendations for work necessary to adequately define the quantity and quality of sand that could be mined on the inner shelf are:

(1) Conduct a synoptic vibratory coring program, using a vibracore capable of obtaining 6 m of continuous core, for the entire inner shelf and along selected transects perpendicular to the shoreline out to a water depth of about 100 m. This coring phase should be integrated with a simultaneous bulk sediment sampling program and 3.5-kHz high-resolution profiling between coring sites. Precision navigation would be imperative in this and all subsequent phases. Analysis of results from the initial coring program in conjunction with the reconnaissance geophysical survey should allow for delineation of specific borrow sites on the inner shelf.

(2) Conduct a site-specific vibratory coring program in conjunction with an integrated high-resolution geophysical survey of potential sites delineated in (1). Vibracoring would require a system capable of taking 12 m or greater continuous cores (Meisburger and Williams, 1981; Hobbs and others, 1985). Site specific geophysical profiling would be used to "close" the isopachs for each site in conjunction with the 6-m and 12-m cores. At the conclusion of this phase, the most promising inner shelf borrow sites and their quantity and quality of mineable sand would be verified.

(3) Environmental impact assessments and economic feasibility studies should be initiated during (2) as logical precursors to any actual applications of permits for sand mining (Hobbs and others, 1985). Furthermore, a modelling study should be undertaken to address the potential modification of wave energy over inner shelf borrow sites and the resulting effects on sedimentation and erosion. The controversies associated with the southern Monterey Bay sand dredging operations and their effect (if any) on coastal erosion would probably be brought to the forefront by any further interest in sand mining. An adequate resolution to the present southern Monterey Bay sand mining and whether it contributes to/enhances shoreline erosion would in all probability be necessary before inner shelf sand mining for beach nourishment becomes a viable and economically feasible option.

ACKNOWLEDGMENTS

This investigation is the result of a Joint Funding Agreement between the U.S. Geological Survey and the State of California, Department of Boating and Waterways. The program was managed by John Dingler (USGS) and George Armstrong and Ron Flick (Cal. Boating).

REFERENCES CITED

Arnal, R. E., 1971, Marine geology of the Monterey Bay near Moss Landing, in Harville, J. P., ed., Kaiser Refractories Environmental Studies Final Report: Moss Landing Marine Laboratory, Technical Report 71-3, p. III 1-21.

Arnal, R. E., Dittmer, E., and Shumaker, E., 1973, Sand transport studies in Monterey Bay, California: Moss Landing Marine Laboratory, Technical Publication 73-5, 71 p.

Belderson, R. H., Kenyon, N. H., Stride, A. H., and Stubbs, A. R., 1972, Sonographs of the sea floor: A picture atlas: Elsevier, Amsterdam, 185 p.

Bradley, W. C., 1957, Origin of marine terrace deposits in the Santa Cruz area, California: Geological Society of America Bulletin, v. 68, p. 421-444.

_____, 1958, Submarine abrasion and wave-cut platforms: Geological Society of America Bulletin, v. 69, p. 967-974.

Bradley, W. C., and Griggs, G. B., 1976, Form, genesis, and deformation of central California wave-cut platforms: Geological Society of America Bulletin, v. 87, no. 3, p. 433-449.

Chin, J. L., 1984, Late Quaternary coastal sedimentation and depositional history, south-central Monterey Bay, California: Unpublished M.S. thesis, San Jose State University, San Jose, California, 130 p.

Chin, J. L., Clifton, H. E., and Mullins, H. T., 1986, Lake Quaternary seismic stratigraphy and shelf history, south-central Monterey Bay, CA: Poster Session, SEPM Gulf Coast Section Research Conference, Corpus Christi, TX.

_____, _____, and _____, in press, Seismic stratigraphy and late Quaternary shelf history, south-central Monterey Bay, California: Marine Geology.

Clark, R. A., and Osborne, R. H., 1982, Contribution of Salinas River sand to the beaches of Monterey Bay, California, during the 1978 flood period: Fourier grain-shape analysis: Journal of Sedimentary Petrology, v. 52, no. 3, p. 807-822.

Combellick, R. A., and Osborne, R. H., 1977, Sources and petrology of beach sand from southern Monterey Bay, California: Journal of Sedimentary Petrology, v. 47, no. 2, p. 891-907.

Dingler, J. R., Laband, B., and Anima, R. J., 1985, Geomorphology framework report, Monterey Bay: Coast of California storm and tidal waves study: U.S. Army Corps of Engineers, Ref. No. CCSTWS 85-2, 100 p.

Dorman, C. E., 1968, The southern Monterey Bay littoral cell: a preliminary sediment budget study: Unpublished M.S. thesis, U.S. Naval Postgraduate School, Monterey, California, 228 p.

Dupre, W. R., 1975, Quaternary history of the Watsonville lowlands, north-central Monterey Bay region, California: Unpublished Ph.D. thesis, Stanford University, Stanford, California, 145 p.

Evans, J. R., Dabai, G. S., and Levine, C. R., 1982, Mining and marketing sand and gravel, outer continental shelf southern California: California Geology, v. 35, no. 12, p. 259-276.

Fischer, P. J., Kreutzer, P. A., Morrison, L. R., Rudat, J. H., Ticken, E. J., Webb, J. F., and Woods, M. M., 1983, Quaternary shelf deposits (sand and gravel) of southern California: Report FR 82-11, State of California, Department of Boating and Waterways, 75 p.

Galliher, E. W., 1932, Sediments of Monterey Bay, California: California Division of Natural Resources, Division of Mines, Journal of Mines and Geology, v. 28, no. 1, p. 42-79.
Greene, H. G., 1977, Geology of the Monterey Bay region: U.S. Geological Survey Open-File Report 77-718, 347 p.
Greene, H. G., Lee, W. H. K., McCulloch, D. S., Brabb, E. E., 1973, Faults and earthquakes in the Monterey Bay region, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-518.
Griggs, G. B., and Hein, J. R., 1980, Sources, dispersal and clay mineral composition of fine-grained sediment off central and northern California: Journal of Geology, v. 88, p. 541-566.
Griggs, G. B., and Johnson, R. E., 1979, Coastline erosion, Santa Cruz County: California Geology, p. 67-76.
_____, _____, 1983, Impact of 1983 storms on the coastline, northern Monterey Bay, Santa Cruz County: California Geology, p. 163-174.
Griggs, G. B., and Savoy, L., 1985, Living with the California coast: Duke University Press, Durham, North Carolina, 393 p.
Hicks, D. M., 1985, Sand dispersion from an ephemeral delta on a wave-dominated coast: Unpublished Ph.D. thesis, University of California, Santa Cruz, California.
Hicks, D. M., and Inman, D. L., 1987, Sand dispersion from an ephemeral river delta on the Central California coast: Marine Geology, v. 77, 305-318.
Hobbs, C. H., Byrne, R. J., Gammisch, R. A., and Diaz, R. J., 1985, Sand for beach nourishment in lower Chesapeake Bay: Proceedings, Coastal Zone 1985, American Society of Civil Engineers, v. 1, p. 791-811.
Hunter, W. P., 1971, Heavy mineral analysis of selected Monterey Bay cores: Unpublished M.S. thesis, U.S. Naval Postgraduate School, Monterey, California.
Malone, M. J., 1970, A pebble-cobble deposit in Monterey Bay, California: Unpublished M.S. thesis, U.S. Naval Postgraduate School, Monterey, California, 47 p.
Meisburger, E. P., 1972, Geomorphology and sediments of the Chesapeake Bay entrance: U.S. Army Corps of Engineers, CERC Technical Memo No. 38, 61 p.
Meisburger, E. P., and Williams, S. J., 1981, Use of vibratory coring samples for sediment surveys: U.S. Army Corps of Engineers, CERC Coastal Engineers Technical Aid No. 81-9, 18 p.
Monteath, G. M., Jr., 1965, Environmental analysis of the sediments of southern Monterey Bay, California: Unpublished M.S. thesis, U.S. Naval Postgraduate School, Monterey, California.
Moore, D. G., 1960, Acoustic-reflection studies of the continental shelf and slope off southern California: Geological Society of America Bulletin, v. 71, p. 1121-1136.
Moore, D. G., and Shumway, G., 1959, Sediment thickness and physical properties: Pigeon Point shelf, California: Journal of Geophysical Research, v. 64, no. 3, p. 367-374.
Mullins, H. T., Nagel, D. K., and Dominguez, L. L., 1985, Tectonic and eustatic controls of late Quaternary shelf sedimentation along the central California (Santa Cruz) continental margin: High resolution seismic stratigraphic evidence: Sedimentary Geology, v. 45, p. 327-347.
National Ocean Survey, 1981, Map 18685 (Monterey Bay) 1:50,000.

Porter, G. A., Ehrlich, R., Osborne, R. H., and Combellich, R. A., 1979, Sources and nonsources of beach sand along southern Monterey Bay, California: Fourier shape analysis: Journal of Sedimentary Petrology, v. 49, no. 3, p. 727-732.

Powell, C. L., and Chin, J. L., 1984, Faunal evidence for a late Wisconsin sea level lowstand, Monterey Bay outer shelf, central California: (Abstract) Society of Economic Paleontologists and Mineralogists, Annual Midyear Meeting, San Jose, CA, p. 66.

Sayles, F. L., 1966, A reconnaissance heavy mineral study of Monterey Bay beach sediment: University of California Hydraulic Engineering Laboratory Technical Report HEL-2-1620.

Scott, D. A., 1973, AMBAG oceanographic survey, Monterey Bay: Oceanographic Services Preliminary Report, Santa Barbara, California, 137 p.

Sieck, H. C., and Self, G. A., 1977, Analysis of high resolution seismic data: American Association of Petroleum Geologists, Memoir 26, p. 353-386.

Tinsley, J. C., III, 1975, Quaternary geology of northern Salinas Valley, Monterey County, California: Unpublished Ph.D. dissertation, Stanford University, Stanford, California, 193 p.

Weber, G. E., 1981, Physical environment, <u>in</u> Le Bouf, B. J., and Kaga, S., eds., The natural history of Ano Nuevo: Boxwood Press, p. 61-121.

Welday, E. E., and Williams, J. W., 1975, Offshore surficial geology of California: California Division of Mines and Geology, Map Sheet 26, 1:500,000.

Wolf, S. C., 1970, Coastal currents and mass transport of surface sediments over the shelf regions of Monterey Bay, California: Marine Geology, v. 8, p. 321-336.

Yancey, T. E., 1968, Recent sediments of Monterey Bay, California: University of California Hydraulic Engineering Laboratory Technical Report HEL-2-18, p. 145.

Yancey, T. E., and Lee, J. W., 1972, Major heavy mineral assemblages and heavy mineral provinces of the central California coast region: Geological Society of America Bulletin, v. 83, p. 2099-2104.

FIGURE CAPTIONS

Fig. 1 Index map of the Monterey Bay area. Bathymetric contours in meters. Dotted isobath represents the approximate position of the 36-m contour---the western limit of the study area.

Fig. 2 Trackline map of single channel seismic reflection profiles used in investigation. Tracklines with "x" collected in 1981; tracklines with "*" collected in 1985. The 36-m isobath shown is the approximate seaward limit of present commercial sand mining technology. Numbers on tracklines represent approximate locations of profiles used in figures which follow.

Fig. 3 Side-scan sonar record showing folded "bedrock" (arrow) outcropping at the seafloor in the Monterey Bight. Scale lines are 15 m.

Fig. 4 Side-scan sonar record showing rippled sandy seafloor (arrow) in northern Monterey Bay.

Fig. 5 Seismic reflection profile of inner shelf near Santa Cruz. Profile shows the thin and largely acoustically transparent unconsolidated sediment veneer overlying an angular unconformity (marked by arrow).

Fig. 6 Isopach map of unconsolidated sediment occurring in the study area. The inner shelf area to the east of the 36-m isobath is the area within commercial dredging limits. Contour interval is 1.0 m for the shelf north of Monterey Canyon and 4.0 m for the shelf south of Monterey Canyon. Bathymetry in meters.

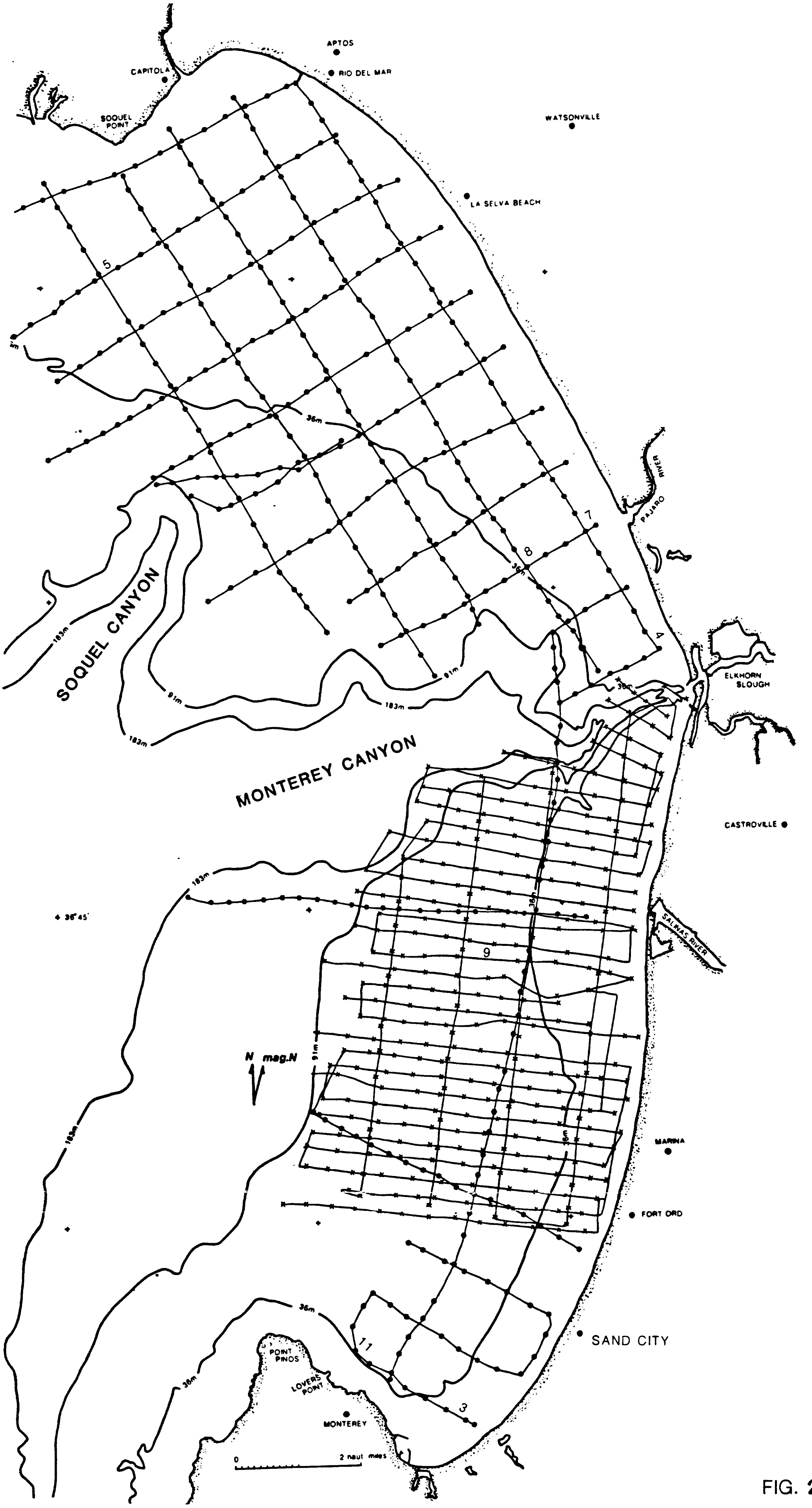
Fig. 7 Seismic reflection profile of the inner shelf of northern Monterey Bay showing thin unconsolidated sediment overlying angular unconformity (arrow) and older deformed strata.

Fig. 8 Seismic reflection profile of the inner shelf off the Pajaro River. Profile shows weakly to parallel bedded unconsolidated sediment lens which overlies an unconformity (arrow). Unconsolidated sediment here is about 10.5 m thick.

Fig. 9 Seismic reflection profile of the inner shelf off the Salinas River. Profile shows fairly-well-bedded unconsolidated sediment lens that overlies an angular unconformity (arrow) and older deformed strata. Unconsolidated sediment here is about 28 m thick.

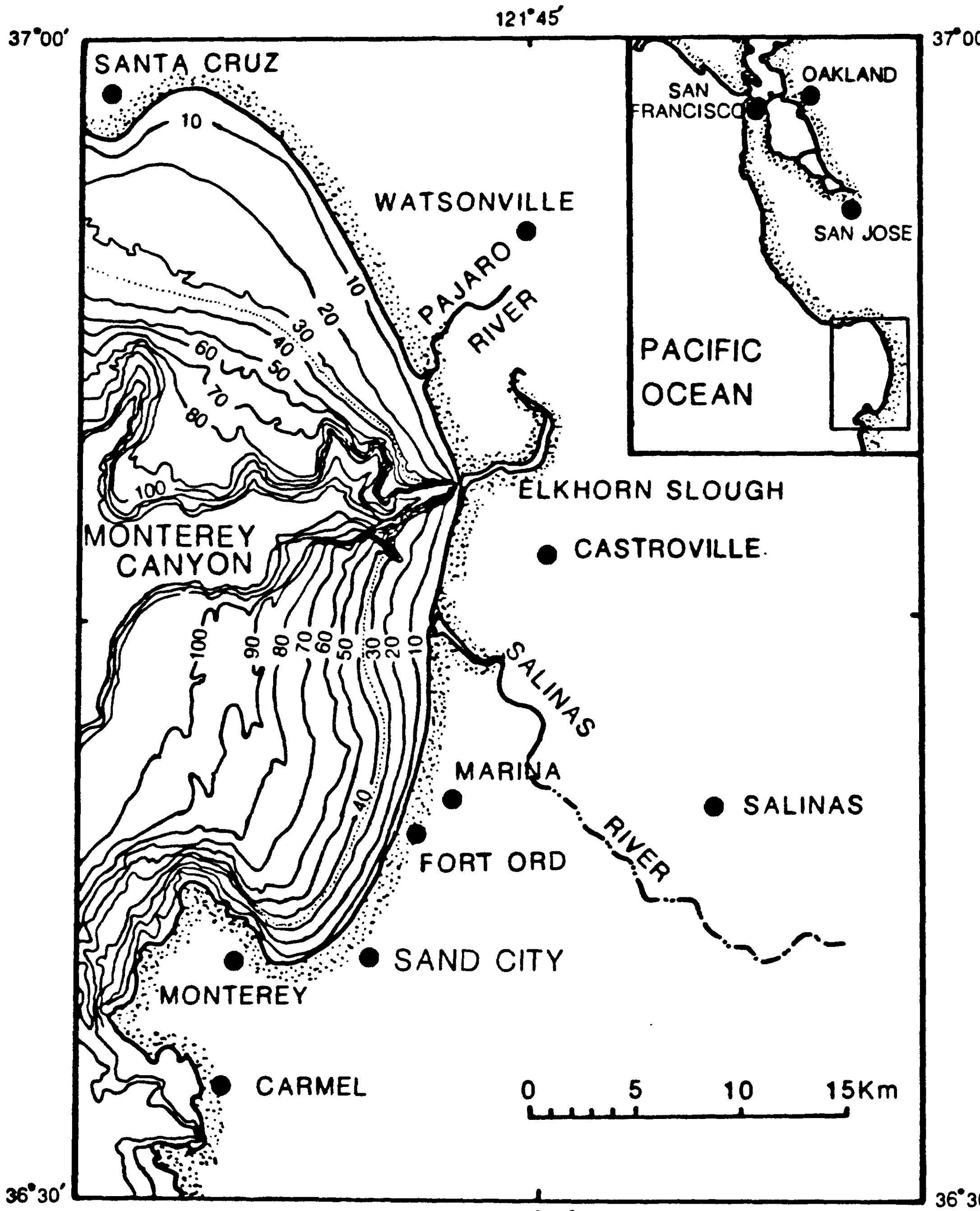
Fig. 10 Structure contour map for the south-central Monterey Bay shelf area. Contours are in meters below present sea level and represent the surface of the angular unconformity. Contour interval is 5 m. Bathymetric contours in meters.

Fig. 11 Seismic reflection profile off the Monterey peninsula showing relatively thick unconsolidated sediment lens overlying an angular unconformity (arrow). Unconsolidated sediment here is about 12 m.



APTOS
CAPITOLA
RIO DEL MAR
SOQUEL POINT
WATSONVILLE
LA SELVA BEACH
5
36m
PAJARO RIVER
7
8
4
SOQUEL CANYON
183m
91m
ELKHORN SLOUGH
MONTEREY CANYON
CASTROVILLE
SALINAS RIVER
9
N mag.N
MARINA
FORT ORD
SAND CITY
11
POINT PINOS
LOVERS POINT
MONTEREY
3
0
2 naut miles

FIG. 2



121°45′
37°00′
37°00′
SANTA CRUZ
WATSONVILLE
PAJARO
RIVER
ELKHORN SLOUGH
MONTEREY
CANYON
CASTROVILLE
SALINAS
MARINA
SALINAS
RIVER
FORT ORD
SAND CITY
MONTEREY
CARMEL
SAN
FRANCISCO
OAKLAND
SAN JOSE
PACIFIC
OCEAN
10
20
30
40
50
60
70
80
90
100
0
5
10
15Km
36°30′
36°30′
121°45′

FIG. 1

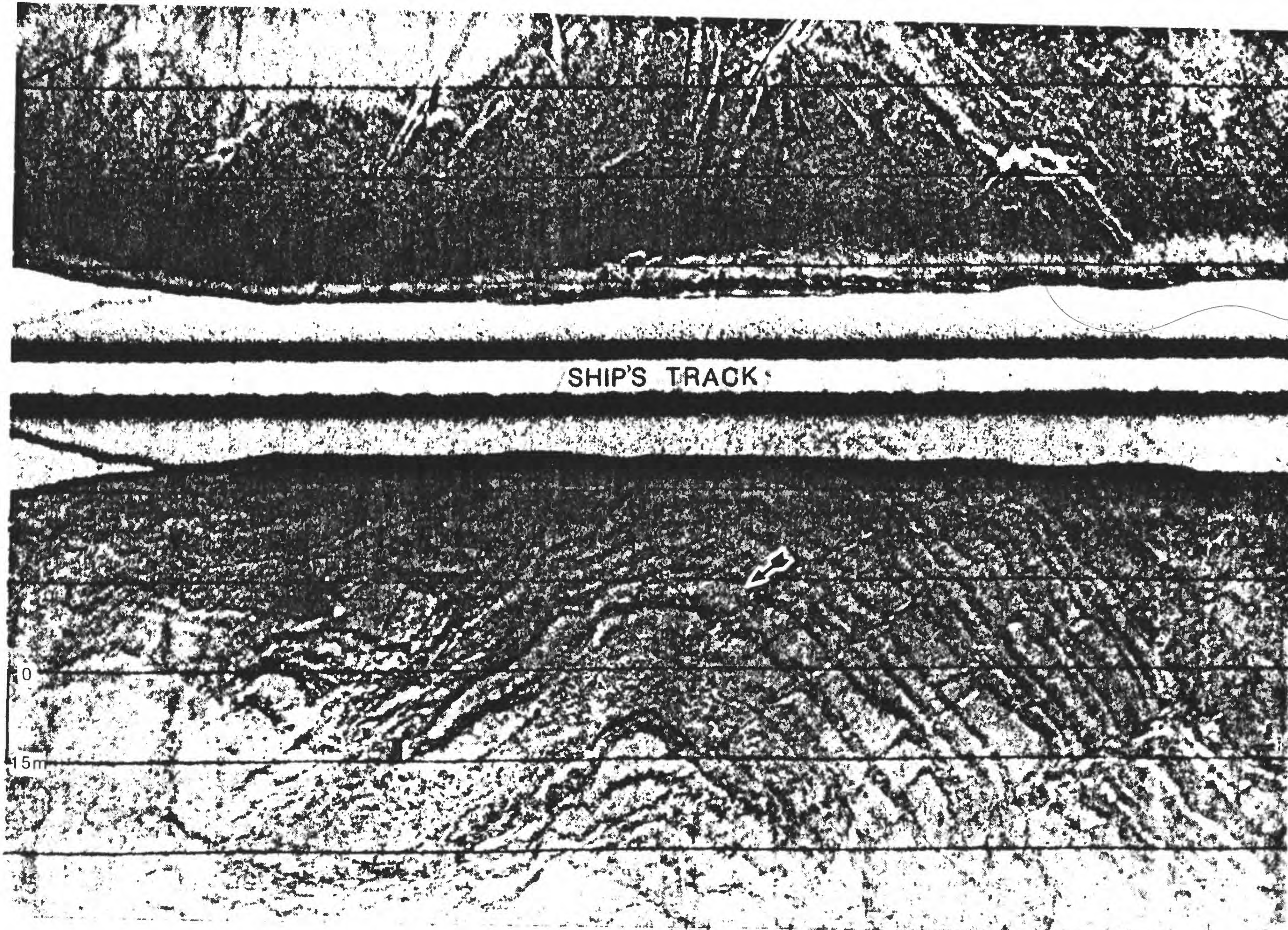


FIG. 3

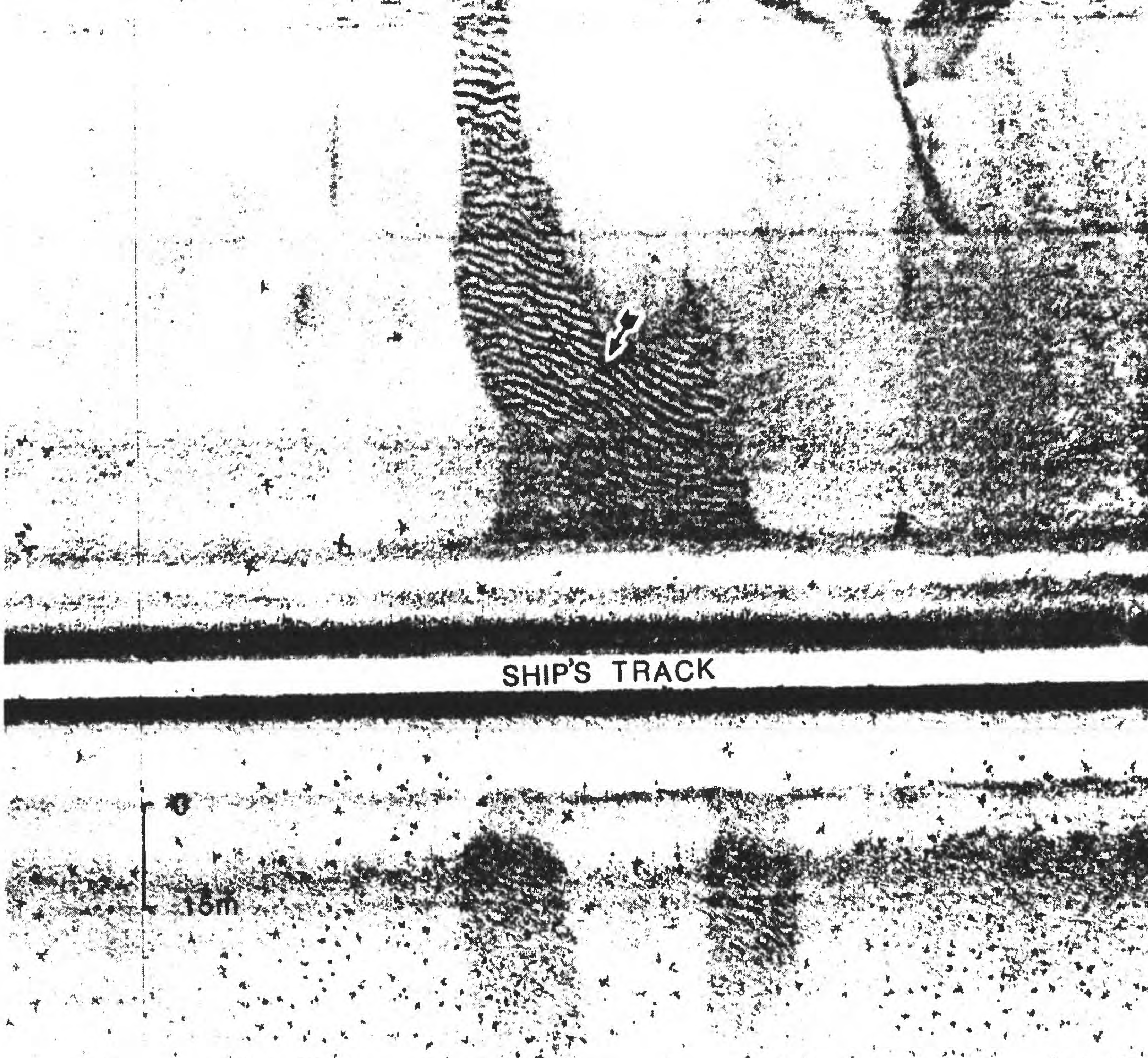


FIG. 4

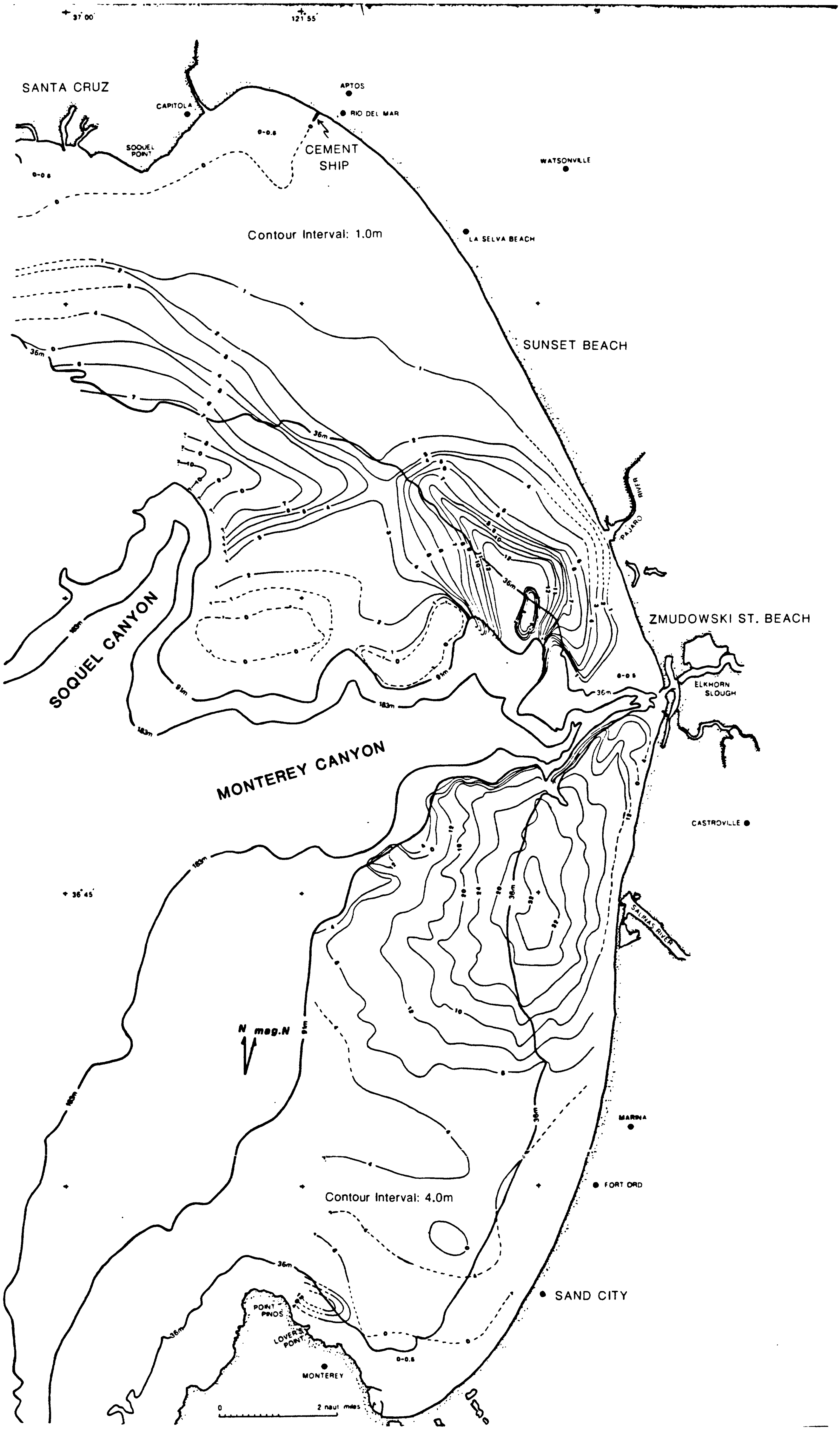

SANTA CRUZ
CAPITOLA
SOQUEL POINT
APTOS
RIO DEL MAR
CEMENT SHIP
WATSONVILLE
Contour Interval: 1.0m
LA SELVA BEACH
SUNSET BEACH
PAJARO RIVER
ZMUDOWSKI ST. BEACH
ELKHORN SLOUGH
SOQUEL CANYON
MONTEREY CANYON
CASTROVILLE
SALINAS RIVER
N mag.N
MARINA
FORT ORD
Contour Interval: 4.0m
SAND CITY
POINT PINOS
LOVER'S POINT
MONTEREY
2 naut miles

FIG. 6

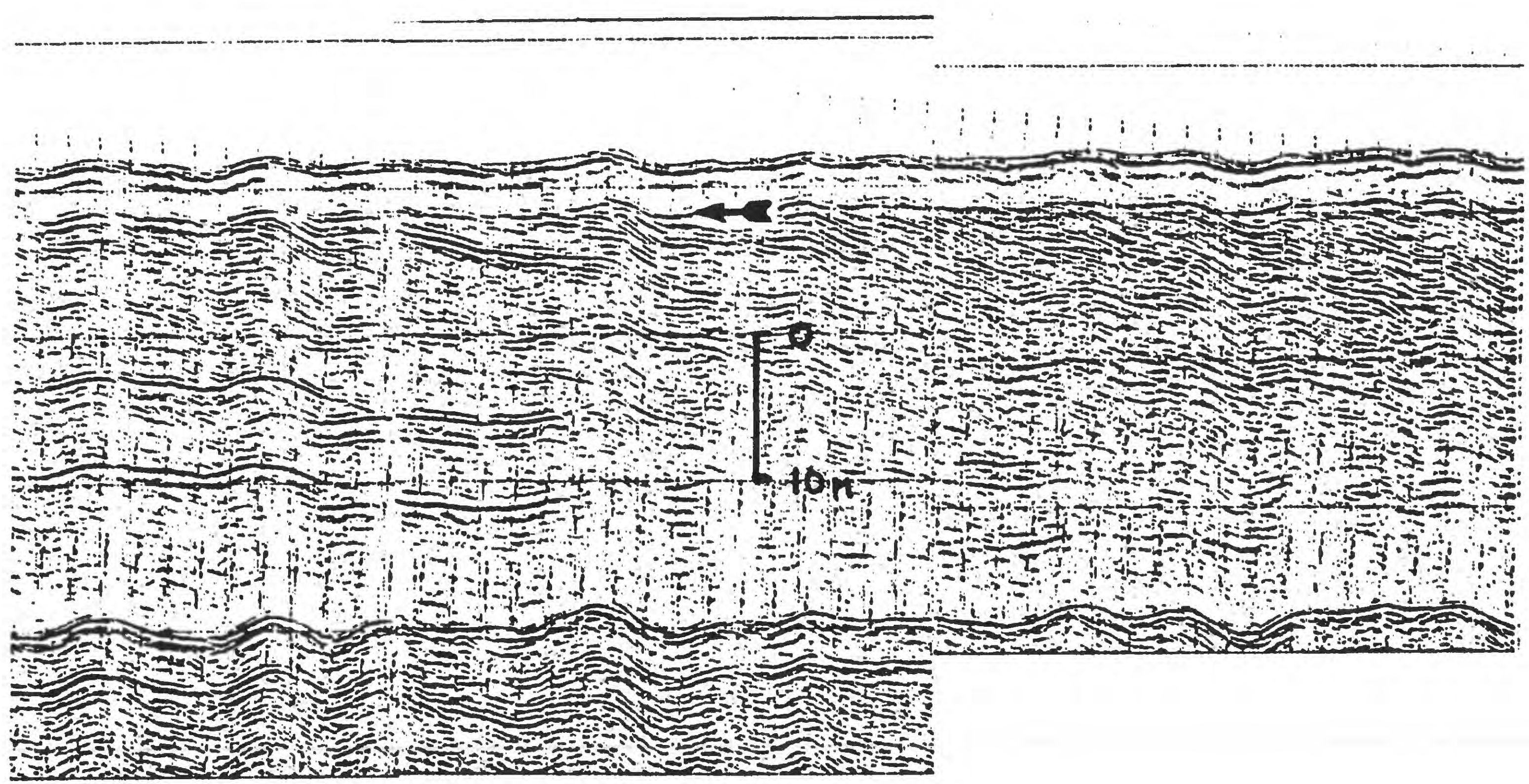


FIG. 5

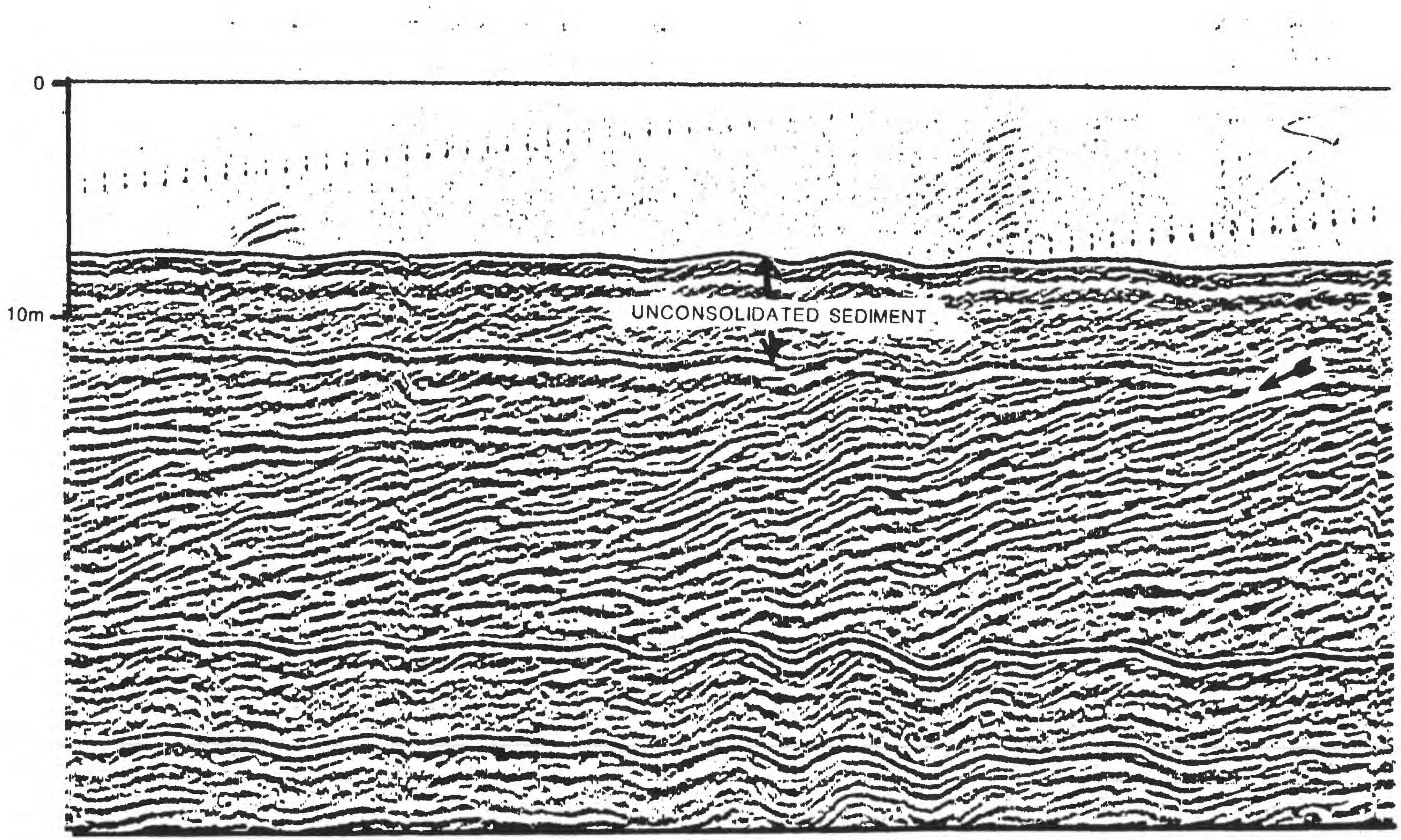


FIG. 7

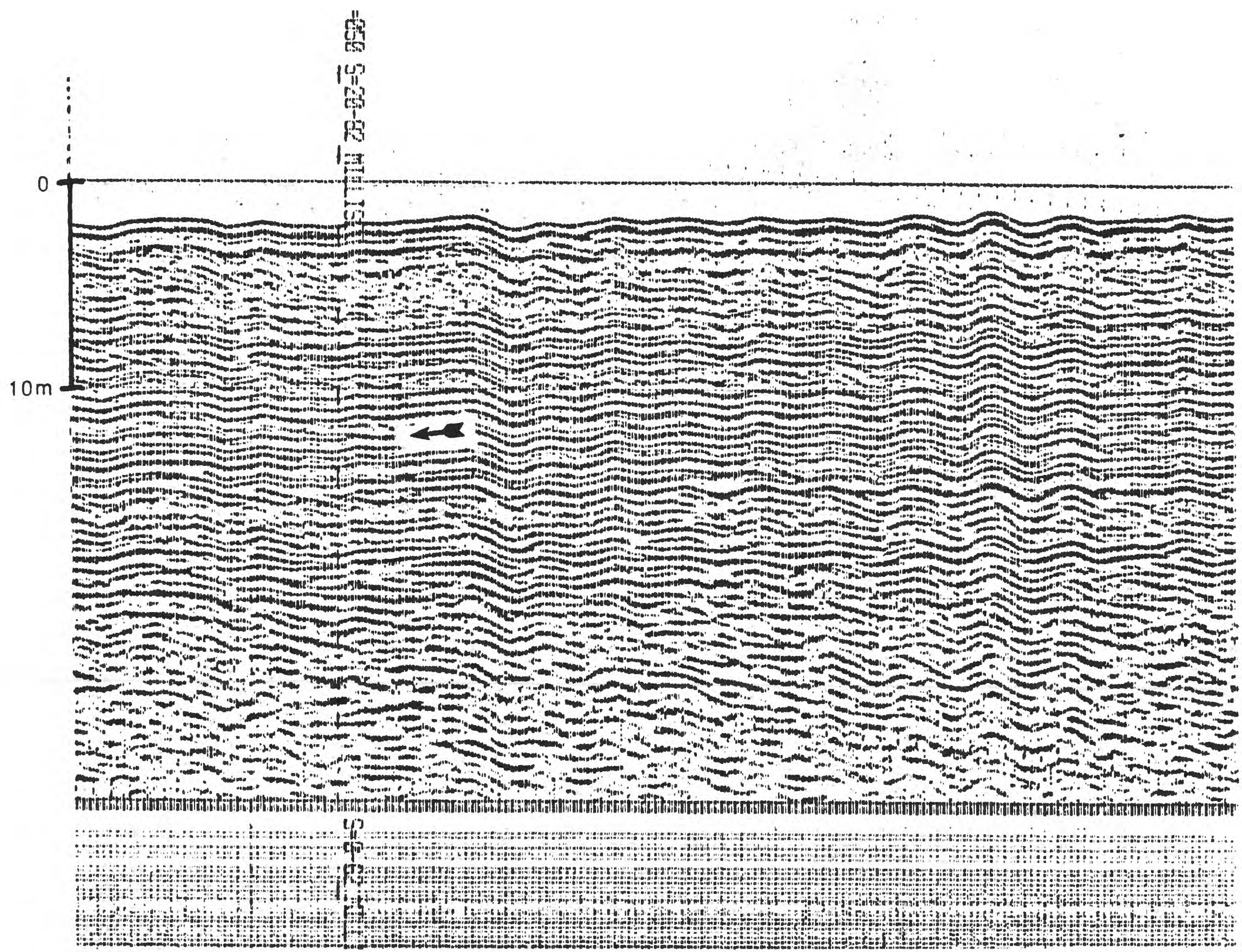


FIG. 8

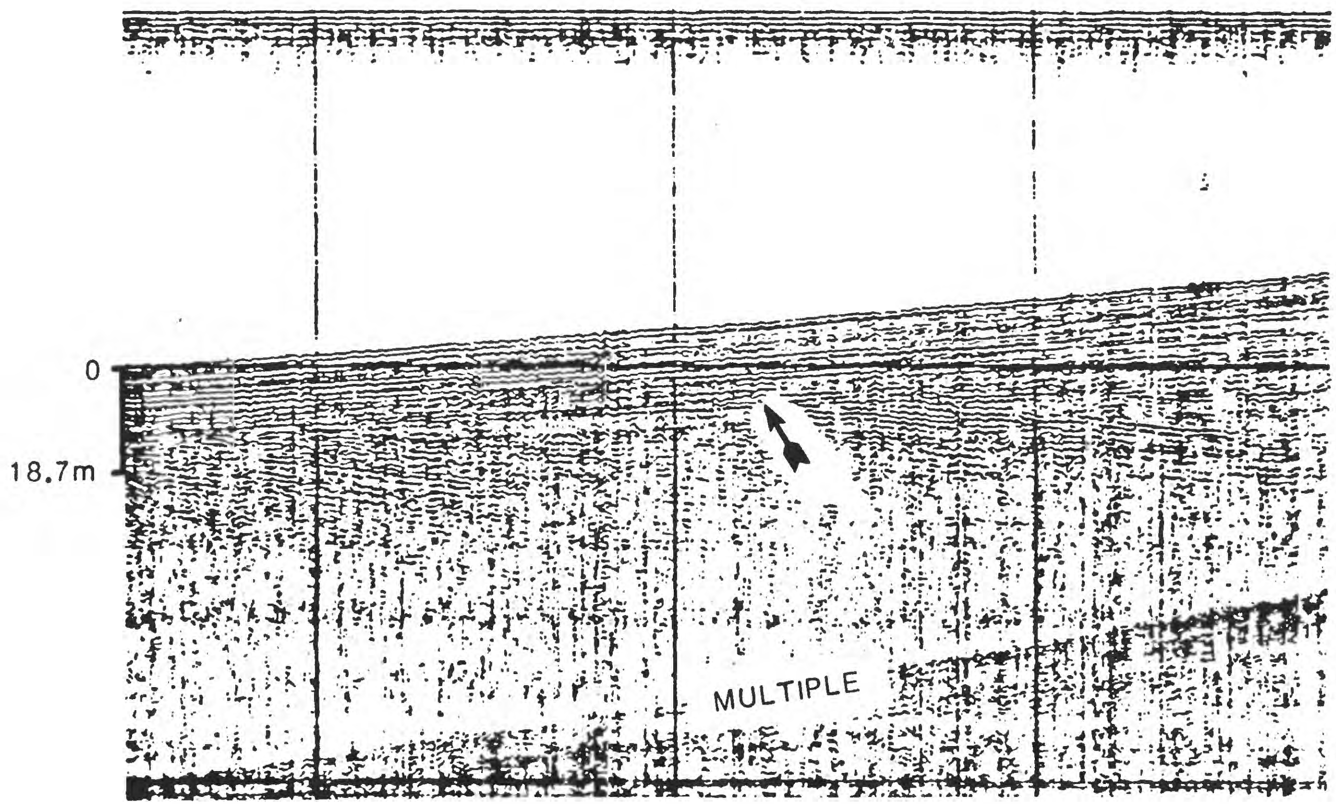
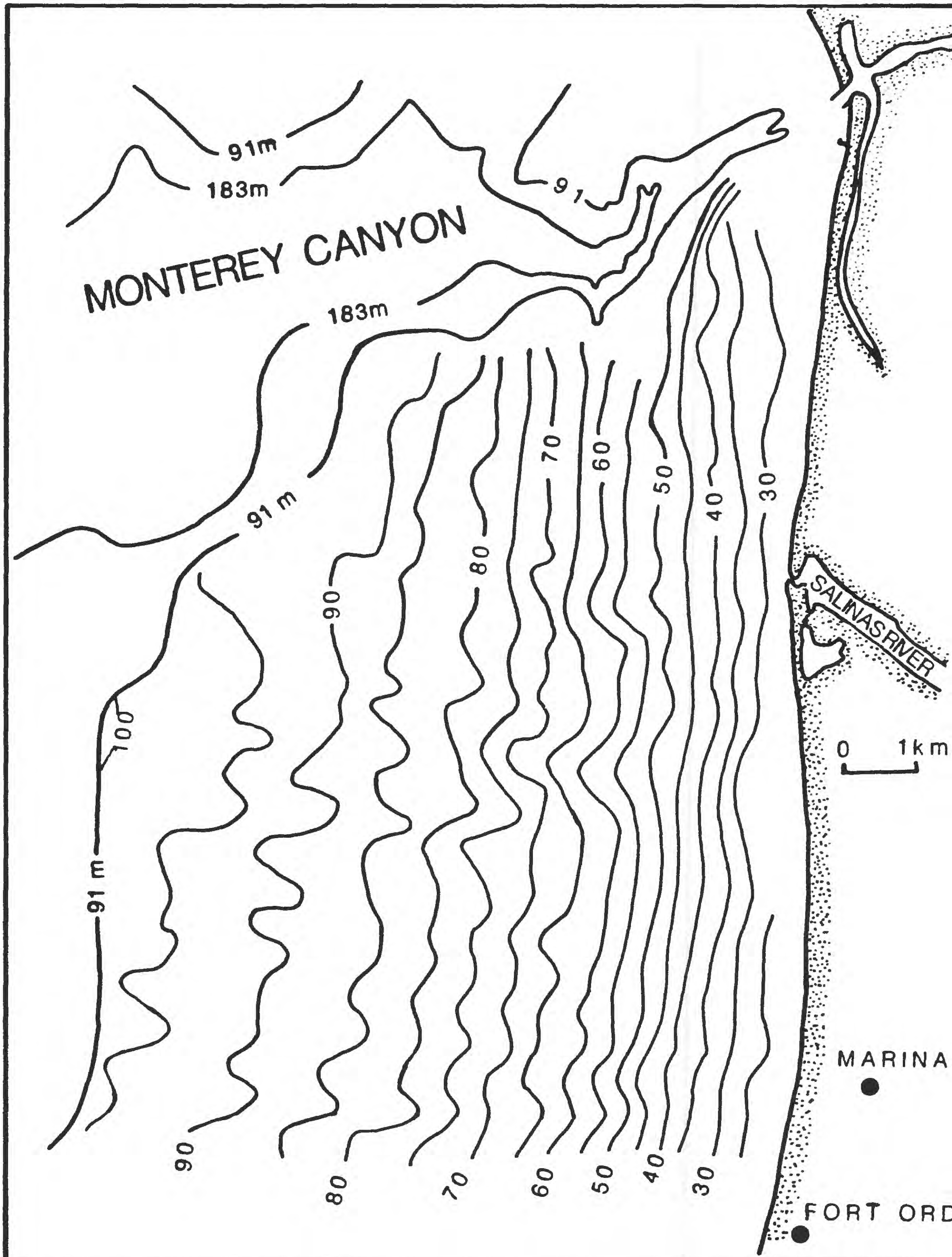


FIG. 9



MONTEREY CANYON
91m
183m
91
183m
91 m
100
91 m
90
80
70
60
50
40
30
SALINAS RIVER
0 1km
MARINA
FORT ORD

FIG. 10

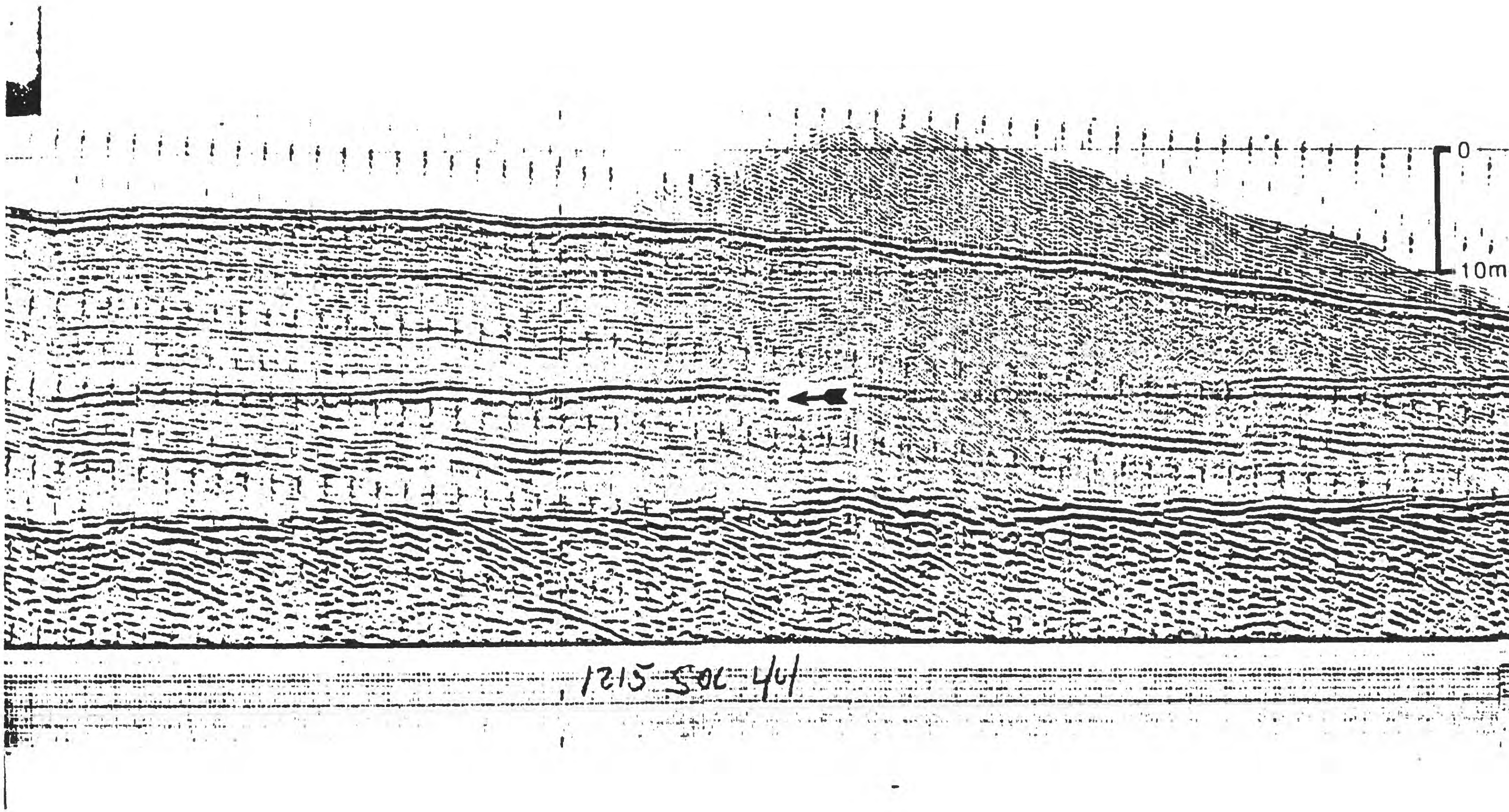


FIG. 11