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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southwest Fisheries Science Center

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ABSTRACT

Characterizations of benthic fish habitat and coastal ocean circulation patterns are critical steps in evaluating the effectiveness of the Big Creek Ecological Reserve at protecting and enhancing coastal fishery resources. With the coordinated efforts of geologists, biologists, and physical oceanographers, geophysical and oceanographic data were collected during a 4-day (3-6 June 1996) research cruise onboard the NOAA ship *McArthur.* We used side scan sonar to survey 24.6 km^2 of the continental shelf along the Big Sur coast in water depths from 30 to 200 m, and created maps of bottom types. We identified and quantified eight types of potential benthic habitats, ranging from sediment ripple fields with low relief to extensive rock outcrops and isolated pinnacles. About eight percent of the survey area, both inside and outside the reserve, was made up of complex rock bottom types with relatively high relief; these likely are suitable habitats for many benthic species of rockfishes. Our habitat characterizations will help direct future efforts to assess the fishes and their habitat associations within the reserve.

We also characterized patterns of ocean circulation over the continental shelf and upper slope to a distance of 40 km offshore. Upwelling and substantial offshore transport off Point Sur and Lopez Point were evident in temperature, salinity, and current data collected at sea and in satellite sea surface temperature (SST) imagery. Counter to the traditional view of a southward flowing current over the shelf, we found a coherent 10-20 km-wide coastal current flowing northward at a rate of 8-15 cm/sec through the Big Creek Ecological Reserve and extending from the surface to 200 m in depth. This northward flow contributes to convergence and offshore transport of water at Point Sur. This information will help define the physical processes that affect the distribution, transport, and survival of young fishes, and clarify our expectations for recruitment from the reserve to nearby unprotected areas.

Introduction

Marine fishery reserves are being considered as a supplement to traditional fishery management throughout the world (see Rowley 1994; Shackell and Willison 1995, for recent reviews). Reserves serve as undisturbed areas for research on natural populations and as fishery exclusion zones where fishes take refuge from exploitation. In the latter case, harvest refugia often are intended (1) to protect spawning stock, thereby ensuring a supply of new recruits to unprotected areas via larval dispersal; and (2) to enhance yields of fish in unprotected adjacent areas via movements of juveniles and adults out of the refuge. Although fishery reserves are rapidly being established, their effectiveness in fisheries management is poorly understood and refugia concepts largely are untested.

In 1990, four marine ecological reserves were created along the California coast to protect and enhance fishery resources: King Range-Punta Gorda (Humboldt Co.); Big Creek (Monterey Co.); Vandenberg (Santa Barbara Co.); and Big Sycamore Canyon (Ventura Co.). The Big Creek Ecological Reserve (BCER) is about 8 km^2 in area and located within the Monterey Bay National Marine Sanctuary (MBNMS), about 90 km south of Monterey. This reserve has been closed completely to harvest activity since January 1994, and affords a valuable research opportunity to evaluate some of the anticipated benefits of marine protected areas. BCER may provide an especially good opportunity to study the role that harvest refugia may play for rockfishes, one of the most heavily exploited groups of fishes in central California. Harvest reserves are considered to be beneficial to species that are overfished, reach great sizes or ages, and have limited movements or sedentary behavior. All of these criteria apply to several species of benthic rockfishes.

There are about 57 species of rockfishes off California, and their habitat associations are likewise diverse. Rockfishes live in almost every marine habitat from the intertidal zone to depths >700 m. From our previous research, using side scan sonar, bottom profiling, and a manned submersible to identify and characterize large-scale (i.e., 100's of meters to kilometers) and small-scale (i.e., 1 meter to 10's of meters) habitats that support adult rockfishes on the continental shelf and slope (i.e., 50-300 m water depth), we have learned that different rockfish species exhibit affinities for specific demersal habitats (Pearcy et al. 1989; Yoklavich et al. 1993; Yoklavich et al. 1995; Starr et al. 1996). Diversity, quality, and extent of habitat likely are among the most significant environmental determinants of distribution, abundance, and species richness of benthic marine rockfishes (Carlson and Straty 1981; Pearcy et al. 1989; Carr 1991; Stein et al. 1992), and therefore essential to their conservation.

In addition, small-scale oceanographic processes associated with regional wind and ocean current patterns can affect distribution, transport, and survival of young rockfishes in nearshore coastal areas (Sakuma and Ralston 1995; Ralston and Howard 1995; Yoklavich et al. 1996). An understanding of potential transport processes is critical when (1) choosing appropriate sites for marine reserves; (2) evaluating transport and recruitment of young fishes from a reserve to nearby fished areas; and (3) assessing input of beneficial (e.g. nutrients, prey) and harmful (pollutants) materials to a reserve.

In this report we summarize results of a coordinated study among biologists, geologists, and physical oceanographers. Our first objective was to characterize the geology of the seafloor within BCER and unprotected adjacent areas. We used side scan sonar and bathymetric profiles to create maps of bottom types and refine our understanding of regional seafloor geology. From these maps we identified and quantified potential fish habitat. Our second objective was to characterize patterns of ocean circulation in nearshore waters from detailed hydrographic and Acoustic Doppler Current Profiler (ADCP) data. This characterization will help in evaluating potential transport of young pelagic stages of fishes from BCER to surrounding unprotected areas.

Materials and Methods

Geophysical Data Acquisition and Processing

Side scan sonar has proven to be a suitable method for differentiating areas of hard substrata from surrounding soft sediments based on differences in intensity of reflected sound (Able et al. 1987; Greene et al. 1995; Yoklavich et al. 1995). Our side scan sonar imagery (i.e., sonographs) of seafloor morphology resembles the negative of a black and white photograph. Topographic features such as ledges, vertical walls and boulders create dark and light images, depending on the orientation and hardness of the feature. A strong signal (dark) is received from the side of a relatively hard feature facing the transducer, whereas a weak signal or shadow (light) is received from the side sloping away from the transducer.

A side scan sonar survey of BCER and adjacent areas was completed during 3 days (3-5 June 1996) on board the NOAA ship *McArthur* and associated 9-m long skiff. BCER is located in the southern portion of the MBNMS at approximately 36° 03.5' - 36° 05.4' N and 121° 36' - 121° 38' W. We used a 100/500 kHz *EG&G* side scan sonar system to identify and map bottom types within and seaward of BCER and approximately 4 km to the north and south of the reserve (Figure 1). The survey was conducted along eight track lines, each about 13 km long and 200 m apart; the acoustic swath width was 800 m, generally resulting in >100% overlap for mosaic production. Survey depths ranged from 30 to 200 m.

All side scan data were recorded on a thermal printer as well as on digital tapes. Analog sonographs from each track line were integrated with navigation information from a differential Global Positioning System (dGPS) to form a mosaic of the seafloor within the study area. The mosaic was photoreduced by 50% for further analyses. Geologic interpretation of the mosaic resulted in a set of polygons representing predicted bottom types (e.g., rock outcrop, boulder fields, sand ripples, etc.), which were digitized and incorporated into a geographical information system (GIS) using the software program *MapGrafix*. Data entered into the GIS included bathymetry, bottom types, and track lines from the side scan sonar survey and three manned submersible dives made in the BCER area.

The resolution of sensors and accuracy of data sets are important considerations when spatial information is mapped and analyzed. Expected accuracy of the dGPS was approximately 1-2 m.

Side scan data were corrected for distortion due to slant range and ship speed. Quality of the sonographs ranged from very good (largely in shallow water over rock outcrops) to poor (in deep water over canyons). The depth of seafloor features that could be clearly resolved with our side scan system was limited by the length of the conducting cable (125 and 150 m long) in deep water (i.e., >100 m water depth), and by the dense kelp beds in water < 30 m. Uncertainty in interpretation of these acoustic returns was indicated with a '?' on the maps that were created from interpretation of the side scan mosaic.

The heights of pinnacles and isolated boulders were estimated from the length of their shadows as depicted on sonographs, the distance of the feature from the trackline, and the height of the acoustic transducer from the bottom. The resolution of the pinnacles and boulders declined however, with increased distance of the transducer from the bottom (occasionally, as much as 80 m above the bottom). Estimated height was less accurate in those cases. The position of pinnacles and individual boulders may be somewhat inaccurate as well; the side scan mosaic was orthographic but photoreduced, introducing minimal error relative to other sources of error and to the overall scale of the map.

Bathymetric data were collected along the survey tracks using either an Innerspace 448 digital fathometer integrated with dGPS via *Hypack* software (Coastal Oceanographics, Inc. Middlefield, CT) in shallow water, or the *McArthur's* echosounder in deep water. Data from the *McArthur* were corrected vertically and horizontally for transducer placement on the ship, but were not corrected for either wave height, tidal stage, or pitch and roll of the ship. Because these data were from relatively deep water, error introduced by these factors likely is a small percentage of total depth. These data, together with navigational information, were incorporated into a comprehensive map of regional bathymetry, which also included depth and location information from the US Geological Survey and a past research survey (unpubl. data, M. Yoklavich). The data were combined into 100 m by 10 m grids, with the longest dimension oriented along the track line, and contoured using a kriging algorithm in *Surfer* graphics software (Golden Software, Inc. Golden, CO). Isobaths were contoured at 10 and 20 m intervals.

Interpretations from remotely sensed sonographs need to be verified. Direct observations made from manned or remotely operated submersibles provide suitable groundtruth of the side scan images (Greene et al. 1995; Yoklavich et al. 1995). Limited in situ observations of deepwater habitat in and adjacent to BCER were made in September 1994 during three dives using the 2-person *Delta* submersible at three sites. At that time, our primary objective was to locate rock habitats and to estimate fish densities in an area of relatively low fishing pressure off the Big Sur coast, for comparisons with areas that have been heavily and continuously fished for decades (e.g. Portuguese Ledge in Monterey Bay). Our observations of benthic habitats during these dives also served as preliminary groundtruthing of seafloor features identified from our remote side scan sonar survey. Dives were documented continuously with an externally mounted HI-8 mm video camera and verbally annotated by the observer. As these were exploratory, each dive covered as wide a depth range and bottom distance as possible. Dives ranged from 32 to 243 m in depth, and from 0.6 to 1.3 h in duration.

Oceanographic Data Acquisition and Processing

Acoustic Doppler Current Profiler (ADCP) data on water current speed and direction were collected with a *RD Instruments* 200-kHz transducer mounted to the ship's hull. Data were collected continuously along seven track lines (Legs X1-X7; Figure 2a) in a zigzag pattern across the continental shelf and around the perimeter of the greater BCER area, and were recorded as three-minute averages. Current velocities were measured in 8-m depth bins (i.e., between 7-15 m, 15-23 m, etc. water depth) to the bottom or to the limit of the instrument (about 350 m). Navigational information was collected with a GPS receiver. We collected ADCP data from about 1,000 km of track lines during this study.

Calibration of the ADCP was conducted off Point Piños immediately before and one day following our survey. The two resultant calibration coefficients were averaged and applied to the raw ADCP data as per Joyce (1989). The ADCP data also were corrected for ship's velocity using GPS data, and obviously erroneous data points were either removed or corrected by interpolation. Further, data points with a signal-to-noise-ratio < 50% good return in the three-minute averaged ensembles were removed. Finally, the data were smoothed by applying a 25-minute lowpass filter to a reference layer and subtracting the difference from all depths in each ensemble. Details on data processing up to this stage are further elaborated in Rago et al. (1997).

A hydrographic survey in BCER and adjacent areas, as well as in a larger region from north of Pt. Sur (36^{o} 21' N) to Cape San Martin (35^{o} 53' N), also was conducted 2-6 June 1996 on board the NOAA ship *McArthur*. Oceanographic data were collected continuously from 500 m (or within 10 m of the seafloor) to the surface at 33 stations (Figure 2b; Table 1) using a *SeaBird* 911 CTD. Only data collected during the downcast were used. Water samples were collected at the bottom of each cast and used to calibrate salinity estimated from the CTD. The temperature and pressure sensors were calibrated by the manufacturer one month prior to the survey. In addition, a thermosalinometer (TS) collected 10-second averages of surface temperature and salinity throughout the cruise. For more details on processing see Rago et al. (1997).

Density anomalies (1000 kg/m^3) were calculated using the Matlab SEAWATER library(Morgan 1994). Seawater spiciness[1] was calculated as per P. Flament (unpublished manuscript; Dept. Oceanography, U. Hawaii at Manoa, HI 96822). Dynamic height (10/500 m and 200/500 m) was calculated from CTD data.

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1 A state variable for which constant values orient orthogonal to lines of equal density, such as when drawn on a graph of temperature versus salinity. Density increases with increasing salinity or decreasing temperature, and therefore spiciness increases with salinity or temperature. On a constant pressure (depth) surface, relatively high values of spiciness indicate warm and/or salty water, and relatively low values indicate cool and/or fresh water. Along the central California coast, spiciness is useful in discriminating the warm, salty waters of southern origin from the cooler, fresher waters transported south from the subarctic.

Meteorological data were collected at NOAA National Data Buoy Center (NDBC) moored buoy 46028, located 40 km off Cape San Martin (35.8° N, 121.8° W), from 1 January to 30 June 1996. Variables included daily averaged wind speed, direction, and the along-shelf and across-shelf components. Sea surface and air temperatures also were measured at this buoy and time period. Seven relatively clear AVHRR (Advanced Very High Resolution Radiometer) satellite images of sea surface temperatures (SST) in the study region prior to (19-23 May) and following (8-10 June) our surveys were acquired from the NOAA CoastWatch Group in La Jolla, CA.

Results

Habitat

Geologic Setting of Study Area. The Big Creek Ecological Reserve is located in a complex and diverse geologic setting where rapid uplift is occurring along the central California coast. This dynamic tectonic process, the result of oblique convergence of the Pacific Plate against the North American Plate, has built the Santa Lucia Mountain Range and has restricted the full construction of a continental shelf in this vicinity. Thus, BCER is situated on a relatively narrow shelf where bedrock is exposed and coarse terrestrially derived detritus is transported across the shelf into the channels and canyons of the continental slope.

Geology of the coastal part of the Santa Lucia Range adjacent to BCER comprises several thrust faults and sheets that have exposed Mesozoic plutonic igneous rocks, the Jurassic to Cretaceous Franciscan assemblage of rocks (melange), pre-Cretaceous metamorphic rocks, and upper Cretaceous sedimentary (sandstone) rocks (Hall et al. 1979; McCulloch and Greene 1990; Hall 1991). The Sur Fault zone (a major thrust fault) trends NW-SE along the coast, extending offshore at 36° 07.4' N, 121° 37.8' W. The Esalen Hot Springs in this area likely are the result of deep fluid circulation along this fault zone. Because of rapid geologic uplift, steep slopes and easily eroded rocks (e.g. Franciscan melange) are subject to extensive mass wasting, with large and numerous landslides occurring in the coastal cliffs.

Many high-gradient creeks incise the Santa Lucia Mountains, actively eroding the rock and carrying coarse-grained sediment (e.g. boulders, cobbles, pebbles and gravel) to the coast. Some of these eroded materials are deposited on the narrow continental shelf. However, from the sediment channels identified in our side scan sonar records, it is likely that much of this material is transported across the shelf to the continental slope. Coastal landslides in the region likely supply considerable heterogeneous sediments to the shelf as well. The most extensive sediment cover, which includes both sand and fine sediment, within our study area is located offshore of landslides to the south of the reserve (from 36° 02' N, 121° 35' W to 36° 04' N, 121° 36' W).

The onshore geology of the BCER area can be divided into northern and southern provinces. The northern province extends from 36° 07.5' N, 121° 38.5' W (Hot Spring Canyon) to 36° 06.3' N, 121° 37.5' W (Dolan Canyon), and exposed highly folded Cretaceous sedimentary rocks overlie the pre-Cretaceous metamorphic rocks (Hall et al. 1979; McCulloch and Greene 1990; Hall 1991). Here the Sur Fault zone controls the coastline and is either located in the shallow nearshore seafloor or along the shoreline cliffs. Deformation of the sedimentary rocks appears to be the result of previous fault movement along the Sur Fault zone. The southern province extends from Dolan Canyon to beyond 36° 01.3' N, 121° 34' W (Lopez Point). Here the onshore rocks primarily comprise the Franciscan melange, including metavolcanics, Mesozoic plutonic rocks and pre-Cretaceous metamorphic rocks. This province is dominated by mass wasting.

Bottom Types. From the side scan sonar survey, 24.6 km^2 of seafloor were mapped inside and adjacent to BCER from 30 to 200 m water depth (Figure 3a-d). We identified and quantified eight bottom types: fine sediment (particle diameter <0.06 mm); sediment ripples; sand (0.06-2 mm diameter); individual boulders (>0.25 m diameter); boulder fields (e.g., Figure 4a); rock outcrop; matrix of various substratum textures, likely including rock outcrop, boulder, cobble (64-256 mm diameter), pebbles (2-64 mm diameter) and fine sediment; and isolated pinnacles (Table 2). Sand bottom of low relief comprised 8.2 km^2 (or 33%) of the total area, and was located primarily on the shelf inside and south of the reserve (Figure 3c-d). Fine sediment was found on flat areas of the shelf adjacent to sand channels, rock outcrops, and boulder fields, largely north of the reserve (Table 2; Figure 3b). Wave, current, and tidal energy was sufficient in some areas to produce fields of fine sediment ripples with a north-south orientation (comprising 6% of the reserve area).

About 8% (2.0 km^2) of the total survey area, both inside and outside the reserve, was made up of complex bottom types of relatively high relief (e.g., boulders, rock outcrop, and matrix; Table 2). Two types of rock outcrop were identified. North of BCER, steeply dipping, well-bedded sedimentary rocks, probably equivalent to the Cretaceous sandstone, comprised about 7% of the survey area (Figure 3b). South of BCER, irregular, hummocky rocks equivalent to the metavolcanic Franciscan formation comprised about 7% of the bottom (e.g., Figures 3d, 4b). BCER contained 5% rock outcrop (Figure 3c). A matrix of rock outcrop interspersed with boulders and sediment (Figure 4c) constituted about 1% of the survey area (0.3 km^2). Matrix bottom type likely comprised wave eroded Franciscan rocks and terrestrially derived Franciscan metavolcanic and graywacke boulders, cobbles and pebbles.

We identified at least 49 isolated pinnacles, boulders and outcrops from the side scan sonographs (Figure 3a-d; Table 3). Sixteen of these features had vertical relief $\geq$ 10 m. Mean height of features was 9.2 m (SD = 4.1) and mean width was 32.4 m (SD = 25.2 m). The tallest feature was a 21.6-m tall pinnacle. Most isolated pinnacles and boulders were located within the matrix bottom type, but a few occurred within the rock outcrop bottom type or isolated in sand or sediment habitats (Figure 3 a-d). One such pinnacle, located south of the reserve (Figure 4d), was estimated to be 7 m high and 2.5 m diameter and surrounded by fine sediment in 35 m water depth.

We have successfully used a small manned submersible to groundtruth some of these remotely sensed acoustic images in three areas in and near the reserve. Dive #3466 was 0.7 h duration and transited 3.5 km of fine sediment bottom in 48-108 m of water along the northwest border of the reserve (Figure 3a-c). The dive commenced at the top of a steep canyon slope. The submersible traversed a sediment-covered shelf, heading 140-170^{o}, and entered the reserve from the north. About mid-way through the dive, the submersible changed course (heading 90°) and ascended from 108 to 48 m on a 40-50° slope of shell hash. A field of sediment ripples (0.5-0.75 m wave period) was encountered at 70 m water depth; this field and another one at 90-110 m also were identified remotely in the side scan data. Bottom types encountered during this dive were not appropriate for most adult rockfishes; drift kelp, juvenile rockfishes and lingcod, sea whips and pens were identified from the video.

Dive #3467 was conducted for 1.3 h within the reserve, along a 3.3-km trackline in shallow water (32-53 m; Figure 3a,c). Habitats included sand (56% of time) and a complex of rock (22%) and rock/sand matrix (22%). An isolated rock, about 10 m wide and 5 m high, was encountered at 50 m water depth; this feature also was remotely identified in the side scan sonar data. Extensive rock outcrop (ca. 10 m in height) occurred at 37-47 m depth; a diverse rockfish assemblage was associated with this bottom type.

Dive #3468 was located just outside the southwest boundary of the reserve (Figure 3a,d), commencing in deep water (243 m) at the head of a submarine canyon and traversing upslope to 69 m; dive duration was 0.6 h and transect length was 1.2 km. Bottom type comprised an equal amount of fine sediment (48%) and rock with sediment veneer (52%). Most of this dive was conducted along a nearly vertical canyon wall, alternating between exposed rock and sediment-covered terraces. A dramatic interface occurred at 130 m between rock outcrop below and a less steep sediment slope above. A field of large boulders (ca. 5-10 m diameter) surrounded by sediment was encountered at 123 m. Several species of adult rockfishes were associated with the rock and boulder habitats at all depths; flatfishes and young rockfishes were observed over the sediment. The rock and boulder bottom types observed during this particular dive were not identified in our side scan survey because the restricted length of conducting cable resulted in poor resolution of seafloor images in deep water.

Ocean Currents

Local ocean currents in and around the Big Creek Ecological Reserve were influenced by large-scale changes in weather conditions occurring before and during our study. Perspective in describing these currents can be gained by examining patterns in wind measurements at NDBC buoy 46028, located 40 km off Cape San Martin at 35.8° N, 121.8° W (Figure 2). Because winds are highly coherent along the central California coast (Schwing et al. 1991), measurements at this buoy likely represent winds throughout the survey area.

Winds blowing toward the equator along the coast create offshore Ekman transport that results in upwelling, especially where the coast is oriented with the direction of the wind as is the case off BCER. The upwelling "season" in 1996 began in mid-March, relatively early compared to previous years (cf. Strub et al. 1987). The onset of upwelling is denoted by the switch in winds from a pattern of high day-to-day variability in response to frequent winter storms, to one of persistent upwelling-favorable (southeastward) conditions off central California and a corresponding drop in SST of over 2°C in less than two weeks (Figure 5a).

Distinct pulses in wind speed, with maximum amplitudes approaching 15 m/s, occurred during the 30-day period surrounding our survey (i.e., 15 May -15 June 1996; Figure 5b). The exception was a reversal in the wind direction on 13-16 May, which was accompanied by a 2°C rise in SST. Winds immediately prior to the survey were relatively steady at about 10 m/s, but dropped to 5 m/s on June 1. Winds increased again on June 3 to near 10 m/s, before weakening to less than 5 m/s for the rest of our survey. The decreased along-shelf winds were accompanied by a gradual increase in SST at the buoy (Figure 5b).

The strongest upwelling, as indicated by cold water adjacent to the coast in satellite imagery of SST, often is associated with topographic features such as Point Sur (Breaker and Broenkow 1994; Rosenfeld et al. 1994). Unfortunately, SST imagery was not available during the period of our survey. However, SST imagery was available from 4 days (19-20, 22-23 May) during the two weeks before the survey and from 3 days (8-10 June) immediately following the survey (Figure 6).

Comparing the wind data and the SST images over the same time, a pulsed variability was evident in both wind speed and the rapid response of sea surface temperatures. The first set of images was taken shortly after a brief period of poleward wind (Figure 5b). The onset of upwelling is evident in the May 19 image (Figure 6) as slightly cooler SST (green) from Point Sur to Cape San Martin. Warmest water (red and fuchsia) offshore indicates the variegated eastern edge of the California Current water mass, which moves shoreward during relaxed wind conditions (Rosenfeld et al. 1994). The May 20 satellite image indicates the continuation of relatively strong upwelling, with coldest water (dark blue) extending 30-40 km offshore and south along the coast from Point Sur and Cape San Martin, and the appearance of filaments of cool water flowing offshore near Point Sur and the reserve. This is consistent with Ekman dynamics and the response time of the coastal ocean to changes in wind stress, which is about 19 h in this region.

Weaker winds on May 21 allowed the warmer California Current water to move onshore on the following day (note the return of red coloring in the 22 May image off the Big Sur coast, and into Monterey Bay). The headlands of Point Sur, Cape San Martin, and Point Piedras Blancas, however, continued to be sources of relatively colder water. Stronger winds on May 22-23 resulted in intensified upwelling and cooler SSTs along the coast. Interestingly, even during this mature upwelling event of 20-23 May, relatively warm water (green strip) was evident in the inshore vicinity of the BCER (see especially 20 and 22 May).

The June 8-10 sequence (Figure 6), just days after our survey, was preceded by several days of weakened winds (Figure 5b) and indicates an overall warming of the ocean off BCER (red and fuchsia). This is likely associated with warmer water from the California Current moving onshore as well as from southern California moving northward along the coast, both a consequence of the preceding relaxation event. As wind speed steadily increased from 6 to 9 June, another upwelling event was initiated, as evident in the satellite image of June 10.

The two sets of AVHRR images depict the cycle of upwelling and relaxation typical of central California during summer (Rosenfeld et al. 1994). This is a repeatable pattern; the onset of upwelling events on May 19 and June 6 result in a very similar distribution of SSTs at the same phase of the upwelling cycle. Because the location of cool upwelled SSTs is linked to topographic features (Breaker and Broenkow 1994; Rosenfeld et al. 1994), the spatial distribution of near-surface temperatures can be estimated from recent wind conditions at any time during spring and summer in this area.

If the association between winds and SST, as described above, is applied during our survey, weak winds during June 1-3 should have produced a relaxation in upwelling, with warmer and fresher water of the California Current moving onshore, similar to the images on May 20 and 22. Increased upwelling, with cooler and more saline water near the coast, should have resulted from strengthening winds at the end of June 3 and the strong winds on June 4 (cf. May 23). Weaker winds on June 5 should have produced another relaxation of upwelling on June 6.

The meteorological data and satellite images of sea surface temperatures were used to assist with interpretations of ocean circulation and structure based on the vessel measurements. Ocean current velocities near the surface (15-23 m; Figure 7a), measured with the ADCP, contained a high degree of mesoscale variability. Strong offshore jets with velocities approaching 40 cm/s occurred off Point Sur and south of the reserve (off Lopez Point; 36° 00.8' N, 121° 34' W). A coherent 10-20 km-wide coastal current (8-15 cm/s) flowed north through and adjacent to the BCER, extending from the surface to 200 m and greater (Figures 7a-d; also see Figures 11-15 below). The two offshore jets persisted at deeper depths as well (55-103 m; Figure 7b-c). Water flowed onshore south of Cape San Martin, possibly to replace the offshore flow of water north of the Cape. At depths of 199-207 m (Figure 7d), the flow was still poleward but the offshore jets in the vicinity of the headlands were barely evident. Areas of convergent (divergent) flow were seen south (north) of the offshore jets. Mesoscale (20 km) regions of relatively stronger and weaker flow appeared throughout the area, particularly south of Lopez Point. These may have been caused by tidal, inertial, or other transient phenomena.

Hydrographic measurements of salinity, temperature, density, and dynamic height along the Big Sur coast correspond to ocean current features. Although characterization of near-surface temperature and salinity (Figure 8) is highly complex, the coolest (<10.5 °C), most saline (>33.6 °/oo) waters, a signature of recent upwelling, occurred off Point Sur and Lopez Point. The warmest (>13.5 °C) and freshest (<33.4 °/oo) waters were north of Point Sur and southwest of Cape San Martin, which is consistent with our interpretation that upwelling had relaxed during the latter half of the survey.

The cool, saline signature of upwelling was seen off Point Sur at 59 m as well (Figure 9), while the southern portion of the survey area was fresher and slightly warmer. Temperatures at this depth were of limited range (i.e., 9.2 - 9.6 °C) throughout the area, so variations in salinity controlled the extent of spiciness[1]. Spiciness was lowest off Cape San Martin, largely due to low salinity. High salinity associated with upwelling off Point Sur and Lopez Point contributed to the relatively high spiciness calculated in these areas.

The pattern was dramatically different at depths of 99 m and 199 m (Figures 10-11). Water near the coast was relatively warm and salty, whereas the coolest and freshest water at these levels was offshore. This resulted in an offshore gradient of declining spiciness, with highest anomalies adjacent to the coast. At a depth of 200 m, there was a strong cross-shelf gradient in spiciness (Figure 11). Higher spiciness (warmer and saltier waters) is indicative of water of a southern California origin (i.e., higher percentage of subtropical water). At 200 m, this was constrained to within 10-15 km of shore, coincident with the region of maximum poleward flow. Water of lower spiciness, characterizing the California Current and its relatively higher content of subarctic water, was found offshore in the area where the eastern edge of the California Current is expected to occur.

Dynamic height, both near the surface (Figure 12a) and at 200 m depth (Figure 12b), was higher nearshore than 40 km offshore; this indicates a generally poleward geostrophic flow throughout the upper 200 m over the entire survey region. The geostrophic currents are consistent with the ADCP velocity field.

The relationship between circulation features and water types also can be described from vertical sections of velocity, temperature, salinity, density and spiciness[1] with depth (Figures 13-17). Upwelling can be construed from the isotherms, isohalines and isopycnals sloping up toward the coast in the upper 50 m. In Legs X4 (Figure 14; locations of legs as indicated in Figure 2a), X5 (Figure 15), and X6 (Figure 16), these isolines appear to dome 5-10 km offshore, possibly due to relaxation of upwelling. Off BCER (Legs X5 and X6), nearshore water in the upper 50 m was warm and salty (high spiciness), which coincided with the area of maximum northward flow. This is indicative of southern California water moving northward along the coast. As temperature, salinity, and spiciness at depths >100 m indicate, there was a well-defined, poleward flowing water mass inshore, with a distinct front offshore. Southward flowing water offshore (>10 km) of the reserve had a low spiciness (low temperature and salinity) at depths >50 m, indicative of California Current water. However this water type was relatively warm and fresh near the surface. In between these California Current and Southern California water types, water was relatively cool and saline, suggesting that it had been recently upwelled and transported to the north and offshore.

Summary and Recommendations

Our study is a first step in the process of evaluating benthic fish habitats in deep water and coastal ocean circulation patterns within and adjacent to Big Creek Ecological Reserve. Results of this study provide the basis for longterm monitoring and management of marine resources in this area. Several critical pieces of information need to be collected, however, before appraising the value of BCER in terms of fish populations.

Habitat. Assessment of fish assemblages associated with these benthic habitats is of primary importance in evaluating the effectiveness of BCER to protect and maintain local fish resources. Our characterization and maps of bottom types from remotely sensed acoustic images will assist in planning appropriate in situ surveys to identify and quantify these fishes. Describing both species- and developmental stage-specific use of habitats will be necessary in determining BCER's value to coastal resource protection.

Groundtruthing or verification of our interpretation of the side scan sonar data is an essential step in characterizing fish habitats of BCER. Although we have made limited in situ observations of benthic habitats in three areas in and around BCER during one short submersible survey, specific features that were described from our comprehensive maps of the seafloor, including type, relief, size and spatial distribution of boulder fields, rock outcrops, sediment/rock matrix, etc., need to be revisited using a manned submersible or remotely operated vehicle (ROV). In situ observations also will provide information about the lithology and morphology of rock bottom types. Highly irregular rock surfaces, for example, provide more habitat for some rockfish species than smooth rock (Pearcy et al. 1989; Stein et al. 1992; Yoklavich et al. 1993). From in situ inspections of predicted bottom types, we can more accurately describe and quantify fish habitats in the BCER vicinity.

Results of the side scan sonar surveys and observations from one of our previous submersible dives suggest that the heads of submarine canyons just seaward of BCER may contain more rock habitats, and hence more rockfishes, than are located in the reserve. Because resolution of seafloor images in the deepest parts of our survey (i.e. >100 m) was poor, we have only hints of hard surface and rock exposures in these areas (see ?'s on Figure 3a-d). Additionally, rock and boulders comprised 52% of the bottom types identified during the submersible dive in the head of a canyon to the southwest of the reserve; these potential habitats were not detected in our side scan sonar data from this area (Figure 3a,d), due to restricted length of the conducting cable. For these reasons, we recommend an additional side scan sonar survey specifically focused on the assessment of deeper bottom types outside BCER. It might be beneficial to extend protection to those areas in deep water adjacent to the reserve that provide extensive habitat for rockfish resources.

Temporal change in benthic habitats located along this geologically dynamic coast and the consequences to associated fish assemblages also need to be addressed in determining expected benefits of the reserve. For example, our survey defined large areas of sand and fine sediments, the distribution and extent of which can vary seasonally and annually depending on the magnitude of winter storm activities (Langton et al. 1995). Associated with the influence of storms on the seafloor, low relief rocky bottom types may be seasonally covered with sand and alternately exposed. In addition, considering the steep relief and high elevations of adjacent mountainous areas that receive significant rainfall, onshore erosion can result in the transport of coarse terrestrial detritus onto the narrow shelf area of the reserve and the subsequent alteration of bottom types. These bottom types, which at first impression seem to be static, could represent fish habitats of a seasonally dynamic nature. In situ surveys conducted over several years would be valuable to evaluate seasonal and interannual variability in fish density and habitat associations. Comparable data collected from California's four ecological reserves also would add to our understanding of the spatial heterogeneity of habitat use and provide a comprehensive baseline to monitor and evaluate the functions of these protected areas.

Regional Ocean Circulation and Structure. Strong offshore jets with maximum speeds of nearly 40 cm/s, extending to depths of 100 m and greater, were observed in association with Point Sur and Lopez Point. Water on the southern side of these jets featured the lowest temperatures and highest salinities in the survey. A coherent 10-20 km wide poleward coastal current (10-15 cm/s) was noted in the ADCP and geostrophic velocity fields along the entire Big Sur coast from the surface to at least 200 m deep. This coastal flow coincided with a region of warm, saline water in the upper 50 m, implying a more southerly source. In the seaward portion of the survey, cool and less saline water consistent with the character of California Current water flowed south. These water types were separated by northward moving water that appears to have been recently upwelled.

We suggest an intriguing conceptual model of circulation along the Big Sur coast, including a persistent and coherent poleward flow and a series of recirculating cyclonic cells that move water and material offshore and return to the coast (Figure 18). While results from our June 1996 survey do not agree with the traditional view of a southward flowing California Current during this time of year (Lynn and Simpson 1987), they are not anomalous. Similar poleward flow over the shelf and slope was noted in this same region throughout 1979 and 1980 (Wickham et al. 1987), during spring and summer of 1981 and 1984 (Chelton et al. 1988) and in October 1995 (Rago and Collins 1995). Hopefully future surveys in this area will further develop and test our conceptual model.

These patterns in ocean circulation likely have significant consequences for fisheries recruitment, larval transport, and the subsequent effectiveness of BCER to enhance fish resources. If these patterns prove to be reliable, we could hypothesize that young fish produced by the spawning stock of adults protected within the reserve will be actively advected north and then offshore at Point Sur. The developing fish could be returned to their nearshore habitat to settle, as is the case for many coastal rockfish species, via the onshore flow that we detected to the south of the reserve.

Understanding the influence of ocean currents and associated physical transport on biological processes, such as larval fish distribution, in the context of a protected area, requires consideration of the behavior, development and ecology of the protected species, and the environmental factors critical to dispersal of their pelagic stages (e.g., onshore/offshore, along-shore, and vertical transport of young fishes). Because these factors can be species specific, identifying those species that might produce pelagic young in the reserve during the time of our survey is critical when evaluating the potential impact of the conceptual model on transport of young fishes.

Rockfish larvae, for example, are among the most prevalent members of nearshore ichthyoplankton assemblages (Moser and Boehlert 1991; Moser et al. 1993), with larval release (parturition) occurring mainly from January to April for many of the species off central California (Wyllie Echeverria 1987). Duration of the pelagic larval and juvenile stages of many rockfish species is typically 4-5 months (Anderson 1983; Woodbury and Ralston 1991). Late larval and young juvenile rockfishes of several species have been found in association with thermal fronts as much as 100-150 km off the central California shelf in spring and early summer months (Lenarz et al. 1991; Larson et al. 1994; Sakuma and Ralston 1995). Some amount of upwelling and associated offshore transport has been suggested to be beneficial to the survival of young stages of rockfishes (Ralston and Howard 1995; Yoklavich et al. 1996). The arrival and subsequent settlement of pelagic juvenile rockfishes in subtidal habitats, such as those within the reserve, may be associated with onshore transport during periods of wind relaxation following upwelling (Larson et al. 1994). The strong offshore jets to the north (off Point Sur) and south (off Lopez Point) of the reserve, and occasional periods of wind relaxation and onshore advection, may be important vehicles for transport of young rockfishes from nearshore source areas and subsequent return to juvenile habitats. Similarly, the poleward flow of nearshore water may provide a return mechanism for "seeding" northern fish populations whose larvae would otherwise be transported well south of settlement habitats by the California Current.

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Table 1. CTD stations occupied 3-6 June 1996 off central California in the Big Creek Ecological Reserve area.

Station Number *	Date (1996)	Time (GMT)	Latitude (°N)	Longitude (°W)	Depth of Cast (m)
30	3 June	21:15	36.02	121.60	45
31		21:41	36.01	121.61	307
32		22:18	35.99	121.63	461
33		23:02	35.98	121.66	503
34		23:52	35.96	121.70	507
35	4 June	00:44	36.00	121.74	503
36		01:43	36.05	121.78	525
37		02:46	36.10	121.81	501
38		03:36	36.12	121.78	505
39		04:29	36.13	121.74	521
40		05:15	36.15	121.72	341
41		05:52	36.16	121.71	99
42	5 June	00:42	35.89	121.49	57
43		01:36	35.88	121.57	443
44		02:37	35.84	121.65	503
45		03:46	35.84	121.74	505
46		04:45	35.93	121.74	509
47		07:17	36.09	121.71	503
48		08:07	36.04	121.67	503
49		08:49	36.07	121.63	83
50		23:42	36.24	121.88	41
51	6 June	00:08	36.21	121.90	345
52		00:44	36.18	121.91	509
53		01:32	36.15	121.93	503

* Stations are numbered as in Rago et al. (1997)

Table 2. Amount of each bottom type (km2 and percent of area) surveyed by side scan sonar to the north, south, in the Big Creek Ecological Reserve and overall.

	North Area			Reserve Area		
Bottom Type	(km^2)	%Total	%Known	(km^2)	%Total	%Known
Sand	0.9	12	13	3.5	46	53
Fine sediment	5.1	68	74	2.1	28	32
Rock outcrop	0.5	7	7	0.4	5	6
Boulder field	<0.1	<1	<1	<0.1	<1	1
Matrix *	0.1	1	<1	0.1	1	2
Boulder	<0.1	<1	1	<0.1	<1	<1
Sediment ripples	0.2	3	3	0.5	6	7
Unknown	0.6	8		1.0	13	
Total	7.5	100	100	7.7	100	100

	South Area			Overall Area		
Bottom Type	(km^2)	%Total	%Known	(km^2)	%Total	%Known
Sand	3.8	40	46	8.2	33	40
Fine sediment	3.5	36	41	10.7	44	48
Rock outcrop	0.7	7	8	1.6	7	7
Boulder field	0.1	1	1	0.1	<1	1
Matrix *	0.1	1	1	0.3	1	1
Boulder	<0.1	<1	<1	<0.1	<1	<1
Sediment ripples	0.2	2	2	0.9	4	4
Unknown	1.1	12		2.7	11	
Total	9.5	100	100	24.6	100	100

* Matrix of rock outcrop, boulders and sediment.

Table 3. Dimensions and shape of isolated rock features identified in side scan sonar data collected off central California's Big Creek Ecological Reserve.

	Height (m)	Width (m)	Shape
	7.8	12	Pinnacle
	7.4	8	Pinnacle
	12.0	28	Pinnacle
	6.0	24	Boulder
	13.5	28	Pinnacle
	18.3	24	Boulder
	7.6	20	Boulder
	9.0	24	Pinnacle
	10.7	36	Boulder
	10.0	20	Boulder
	6.8	8	Pinnacle
	6.0	16	Boulder
	7.7	12	Pinnacle
	5.6	20	Boulder
	17.1	24	Boulder
	16.7	16	Boulder
	10.7	28	Boulder
	6.1	36	Boulder
	5.8	24	Boulder
	16.0	76	Pinnacle on outcrop
	7.4	28	Boulder
	16.7	24	Boulder
	5.0	20	Pinnacle
	12.2	44	Pinnacle
	6.2	32	Pinnacle
	6.7	24	Boulder
	8.0	12	Pinnacle
	21.6	128	Pinnacle on outcrop
	5.0	40	Pinnacle and boulder
	8.0	56	Boulder
	6.0	72	Outcrop
	5.8	12	Boulder
	16.7	20	Boulder
	8.8	112	Outcrop
	12.2	44	Boulder
	9.1	44	Boulder
	11.5	64	Outcrop
	12.5	16	Pinnacle on outcrop
	8.3	48	Outcrop
	6.4	80	Outcrop
	6.1	20	Pinnacle
	5.4	20	Pinnacle
	6.7	16	Boulder
	5.0	40	Outcrop
	5.5	8	Pinnacle
	5.0	20	Boulder
	8.2	20	Pinnacle and boulder
	6.7	12	Pinnacle
	8.9	28	Boulder
Mean:	9.2	32.4	
SD:	4.1	25.2	

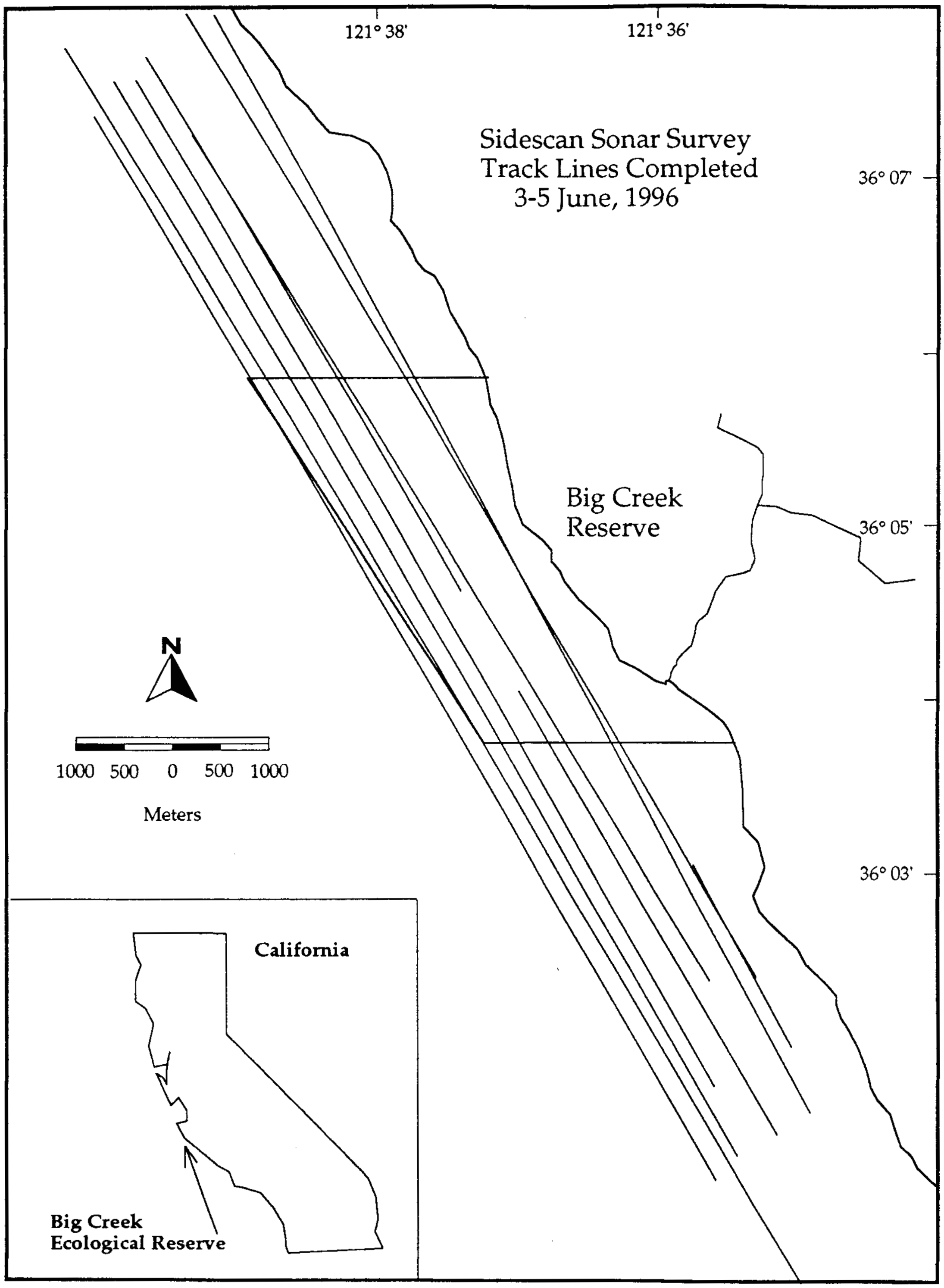

Figure 1. Location of the Big Creek Ecological Reserve and side scan sonar track lines completed during the geophysical survey of potential seafloor fish habitats on board NOAA ship *McArthur*.

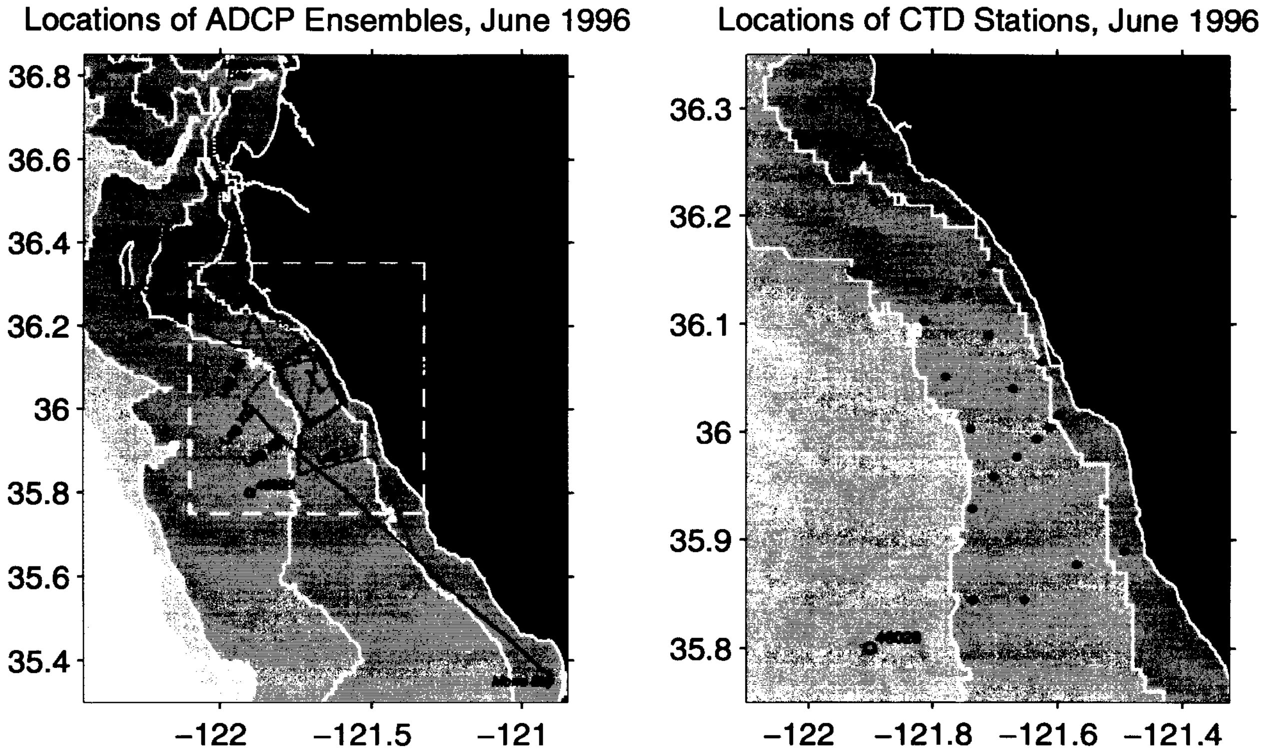

Figure 2. (a) Location of acoustic doppler current profiler (ADCP) survey from Monterey to Morro Bays, 2-6 June 1996. Lines of small dots indicate locations of 3-minute-averaged ADCP ensembles. Seven across-shore legs are labeled. NDBC meteorological buoys at 35.8° N (46028) and 36.8° N (46042) are indicated by open circles. The 200 m, 1000 m, 2000 m, and 3000 m isobaths are plotted and filled. The white dashed box represents the area of CTD stations. (b) Close-up of area of CTD survey. Small open circles indicate positions of CTD stations. Location of NDBC meteorological buoy 46028 is indicated by a larger open circle. The approximate region of the Big Creek Ecological Reserve is shown with a dark fill. The 200 m and 1000 m isobaths are plotted and filled.

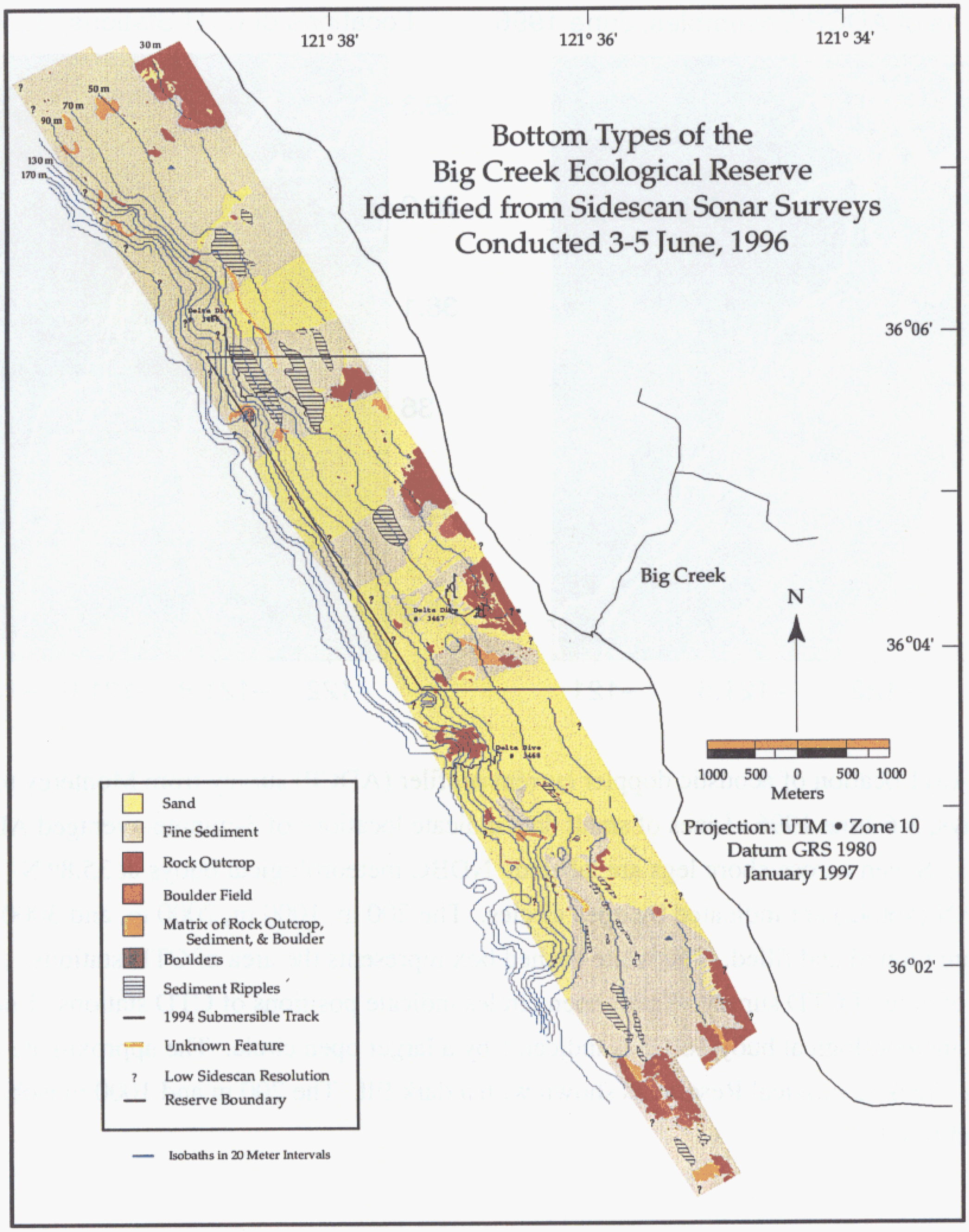

Figure 3a. Map of bottom types of the greater Big Creek Ecological Reserve (boundary indicated) area, as interpreted from a side scan sonar survey conducte 3-5 June 1996. Track lines from three submersible dives conducted in 1994 also are indicated. Question marks indicate areas of low resolution of the acoustic signal (see text). Isobaths are in 20-meter intervals. Table 3 includes estimated sizes of individual boulders and pinnacles.

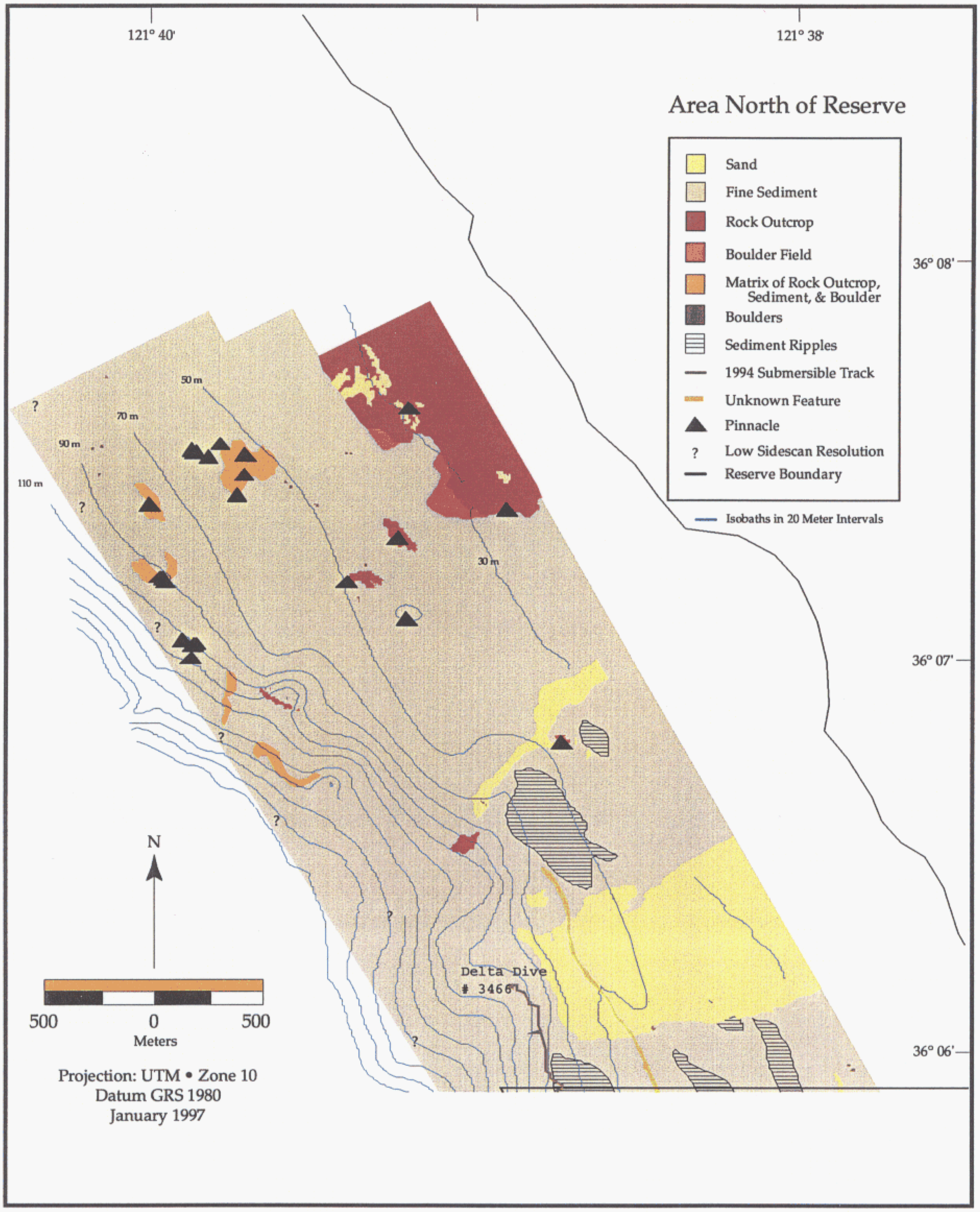

Figure 3b. Enlargement of bottom types in adjacent area to the north of Big Creek Ecological Reserve. See legend of Figure 3a for details.

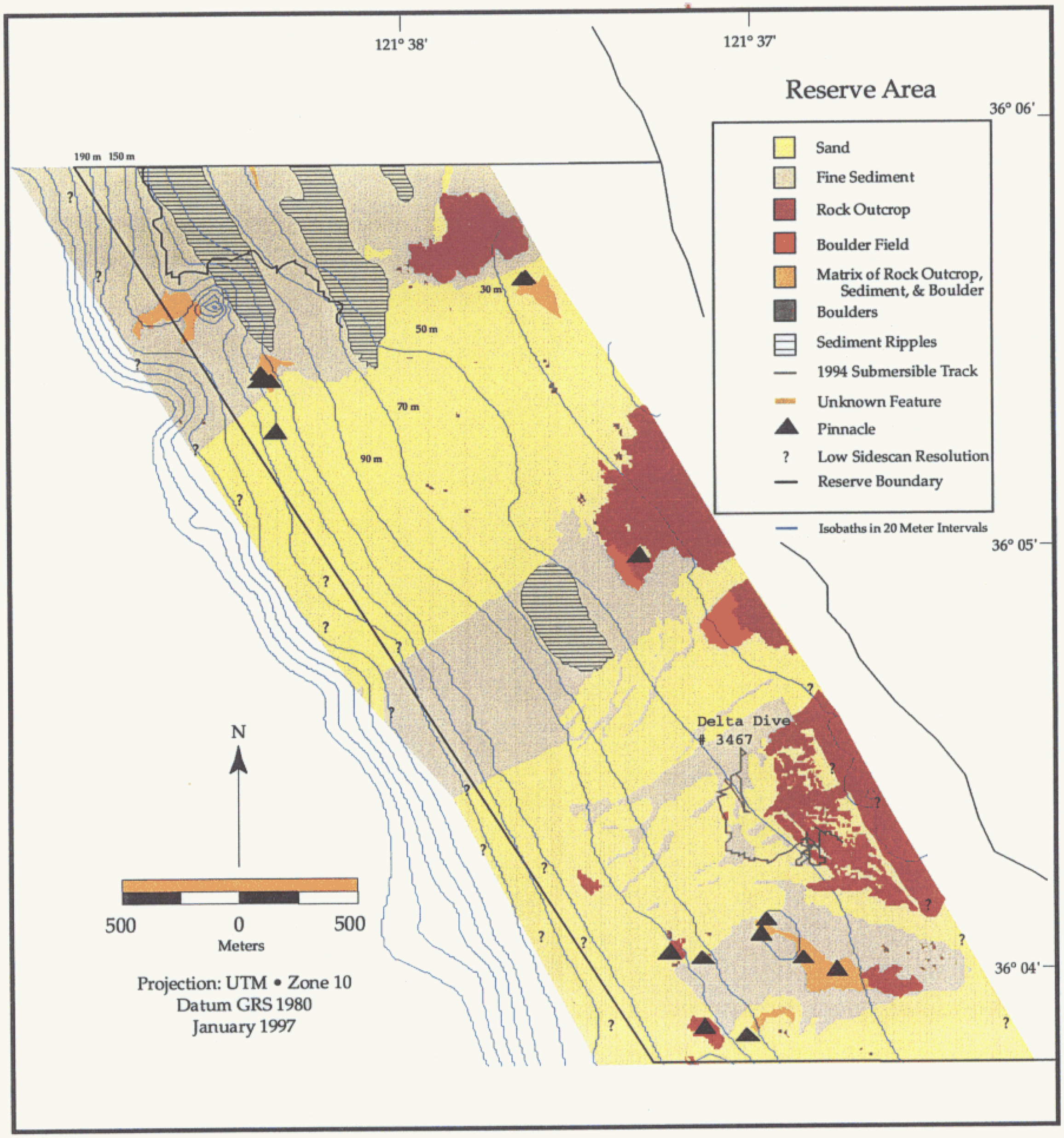

Figure 3c. Enlargement of bottom types within the Big Creek Ecological Reserve. See legend of Figure 3a for details.

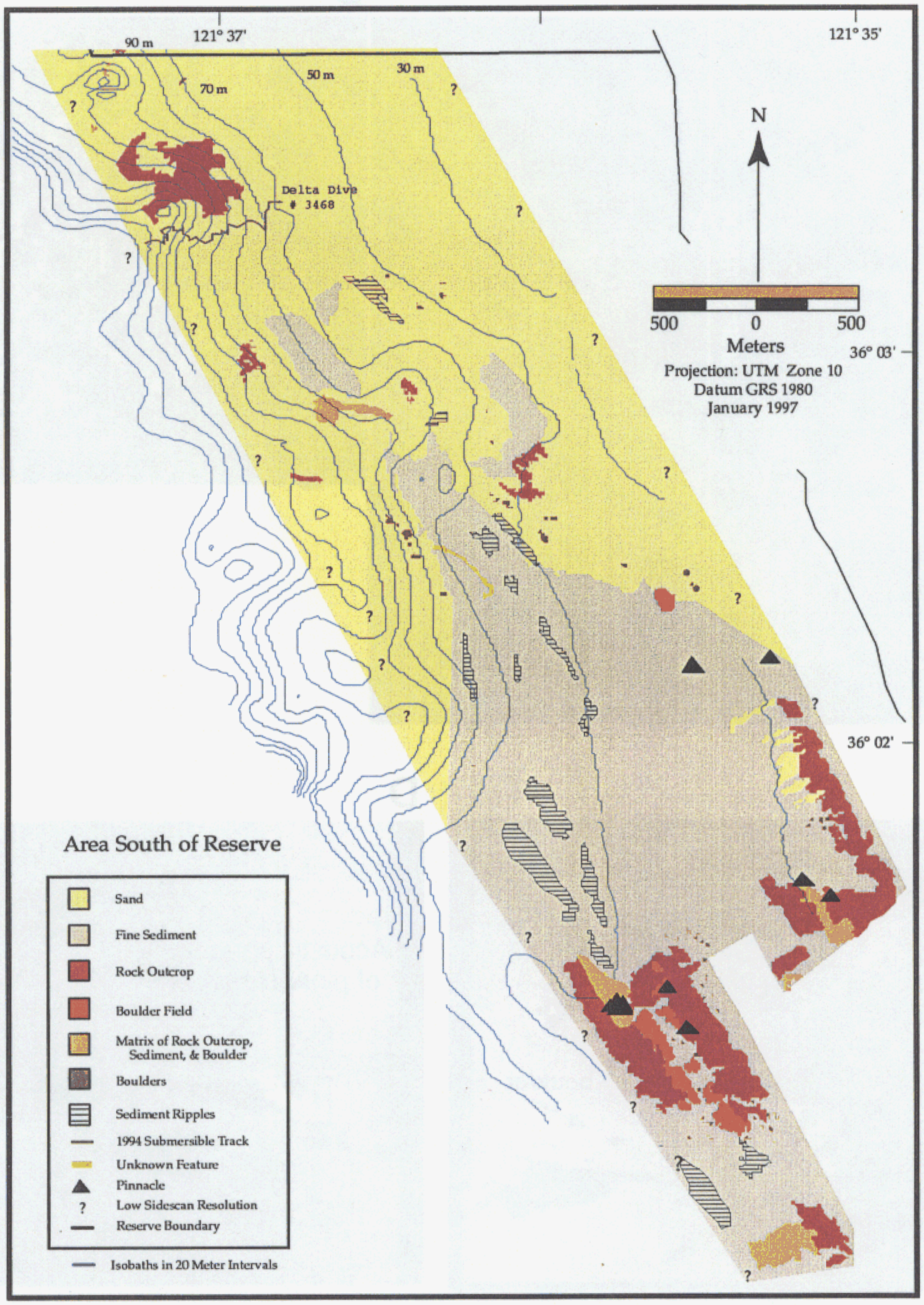

Figure 3d. Enlargement of bottom types in adjacent area to the south of Big Creek Ecological Reserve. See legend of Figure 3a for details.

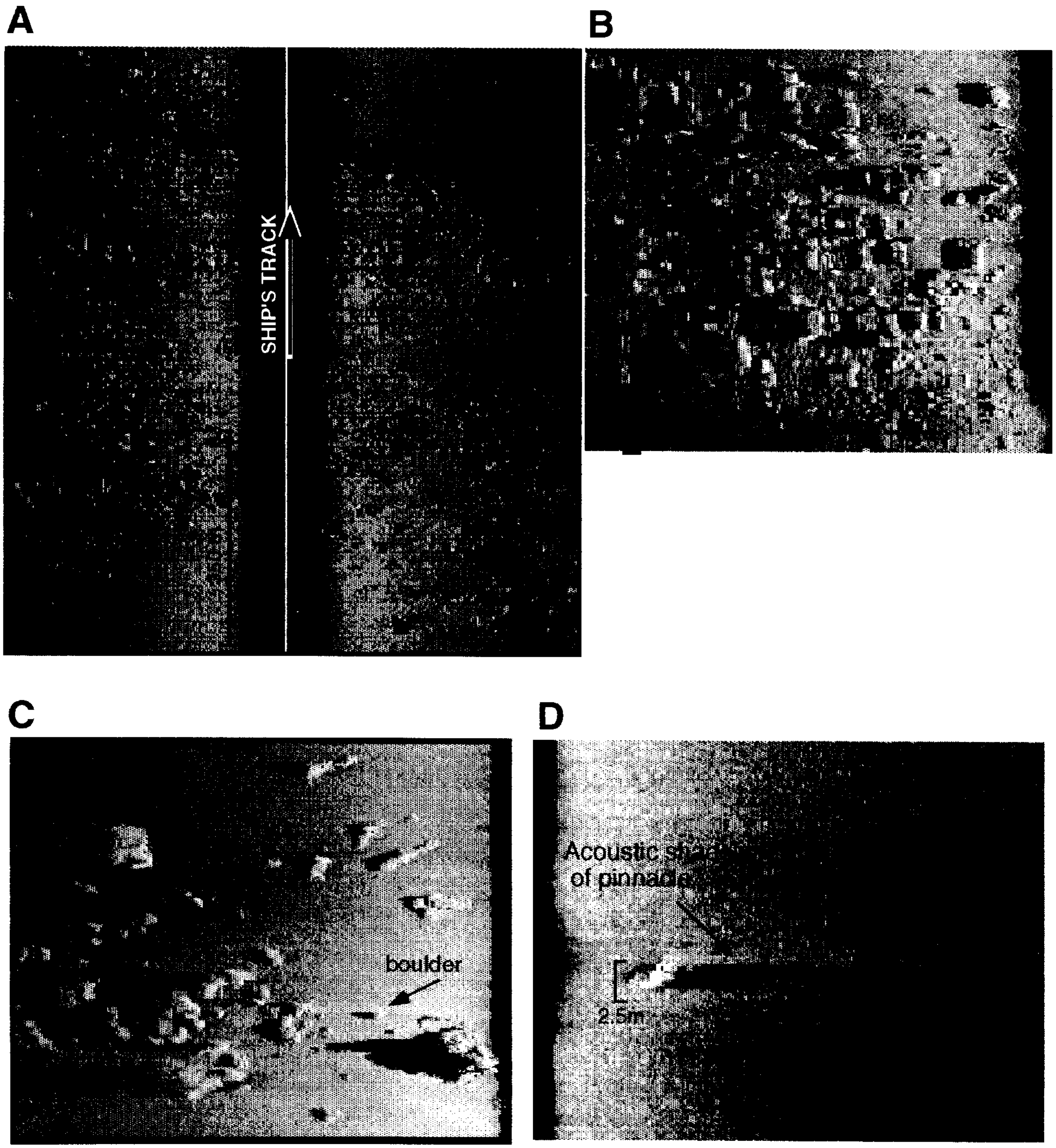

Figure 4. Side scan sonar images (reversed shading) of the seafloor in and around the Big Creek Ecological Reserve. (a) Boulder fields intermixed with fine sediments over a distance of 1 km in 50 m water depth. Sonar frequency: 100/500 kHz; total swath width: 800 m. (b) Example of hummocky rock outcrop in southern part of study site. (c) Matrix of rock outcrop, individual boulders, and fine sediment. (d) Rock pinnacle, up to 7 m high and 2.5 m diameter, surrounded by fine sediment in 35 m water depth located south of the reserve.

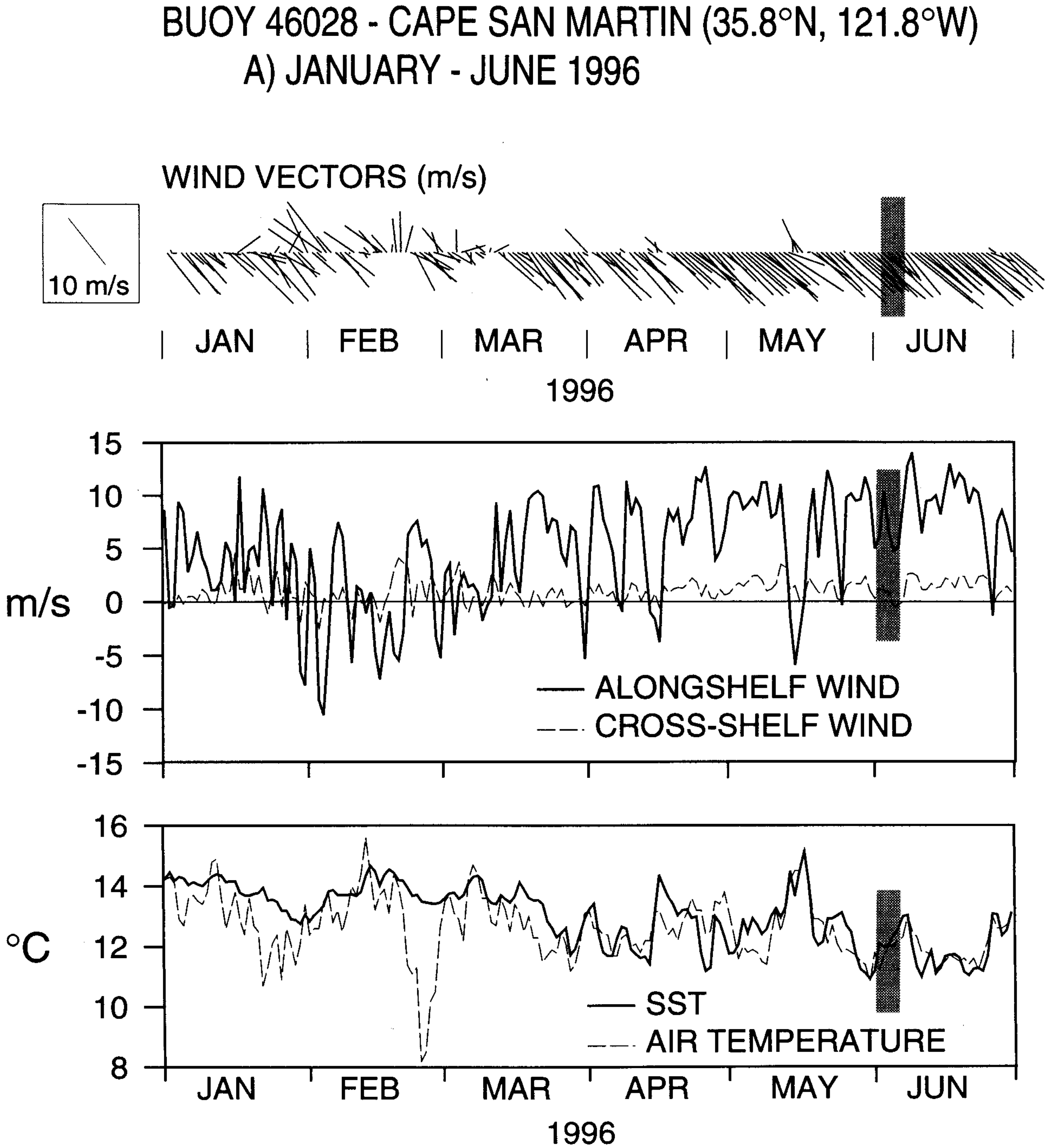

Figure 5a. Time series of meteorological and oceanographic data measured at NDBC buoy 46028 from 1 January to 30 June 1996. (Top) Daily average wind speed and direction (relative to true north); vectors point in direction that wind is blowing. (Center) Along-shelf (plotted as positive along 142 °N orientation) and cross-shelf (plotted as positive along 52 °N orientation) components of wind speed. (Bottom) Sea surface and air temperatures. The survey period is shaded.

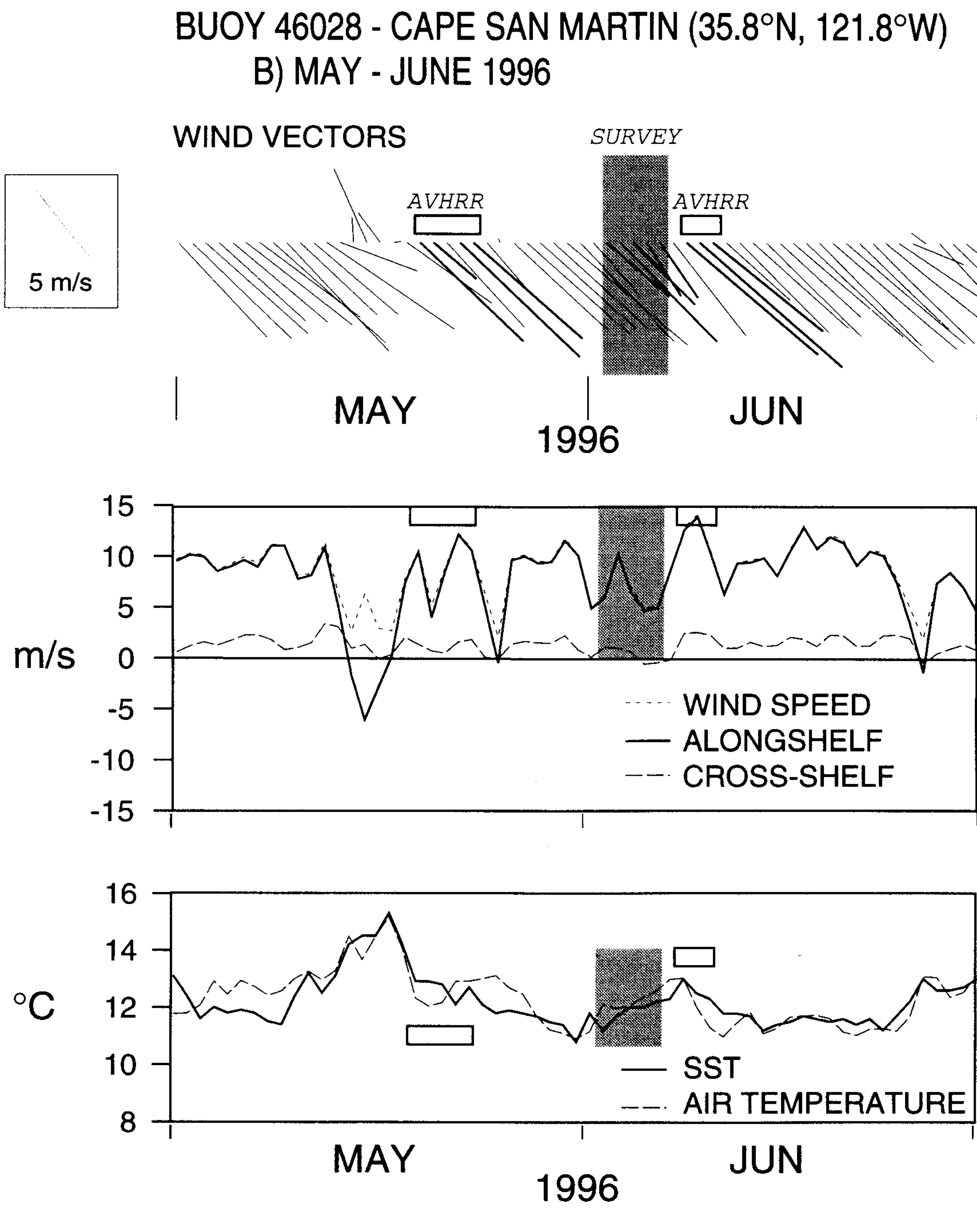

Figure 5b. Time series of meteorological and oceanographic data measured at NDBC buoy 46028 from 1 May to 30 June 1996. (Top) Daily average wind speed and direction (relative to true north); vectors point in direction that wind is blowing. (Center) Along-shelf (plotted as positive along 142 °N orientation) and cross-shelf (plotted as positive along 52°N orientation) components of wind speed. (Bottom) Sea surface and air temperatures. The survey period is shaded and AVHRR sequences (see Figure 6) are indicated by open rectangles.

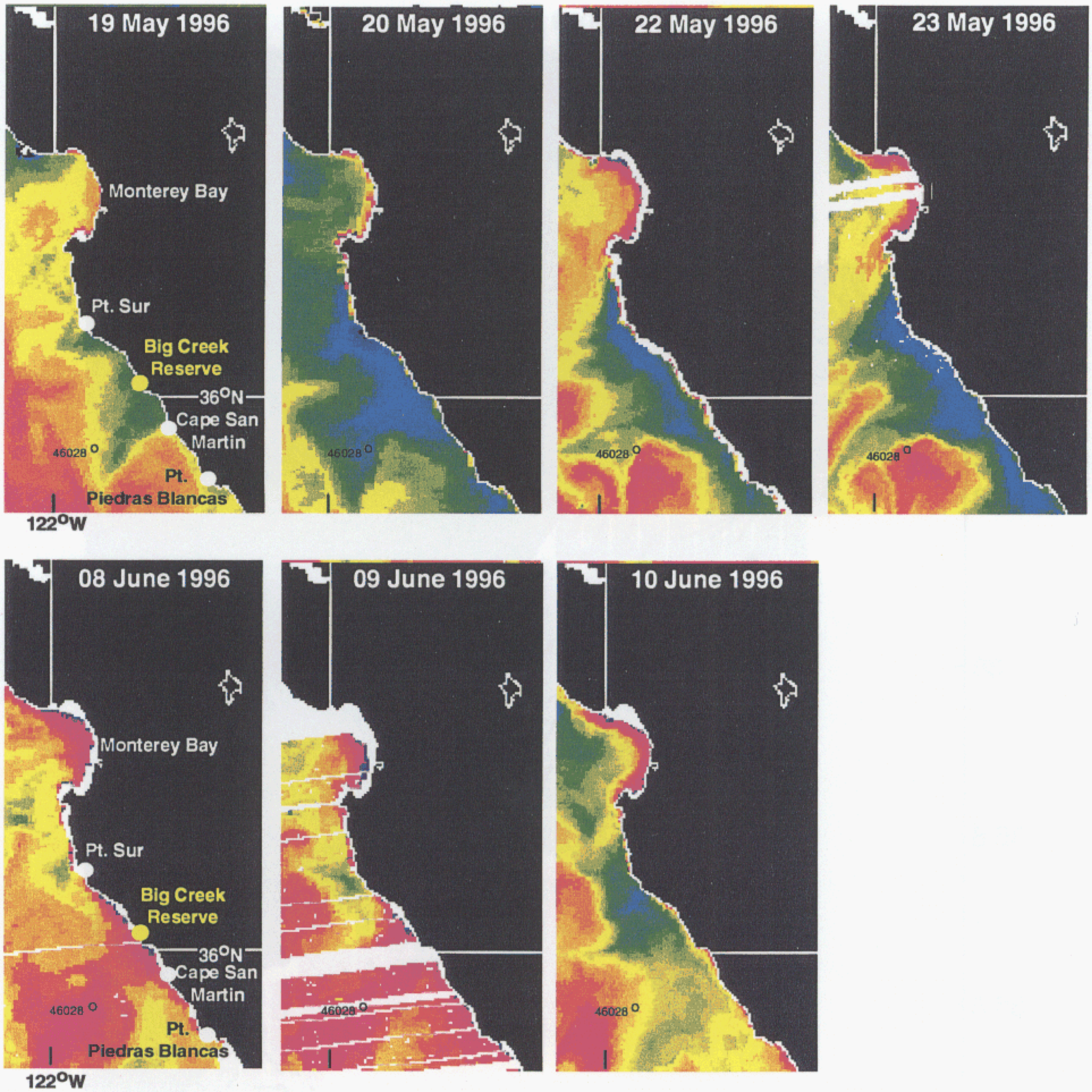

Figure 6. AVHRR satellite images of sea surface temperatures off central California from 19 May to 10 June 1996. A relative color scale is calibrated from coldest (dark blue) to warmest (fuchsia) temperatures. White stripes, especially evident in images on 23 May and 09 June, are due to data loss. Small open circle is location of NOAA NDBC buoy 46028.

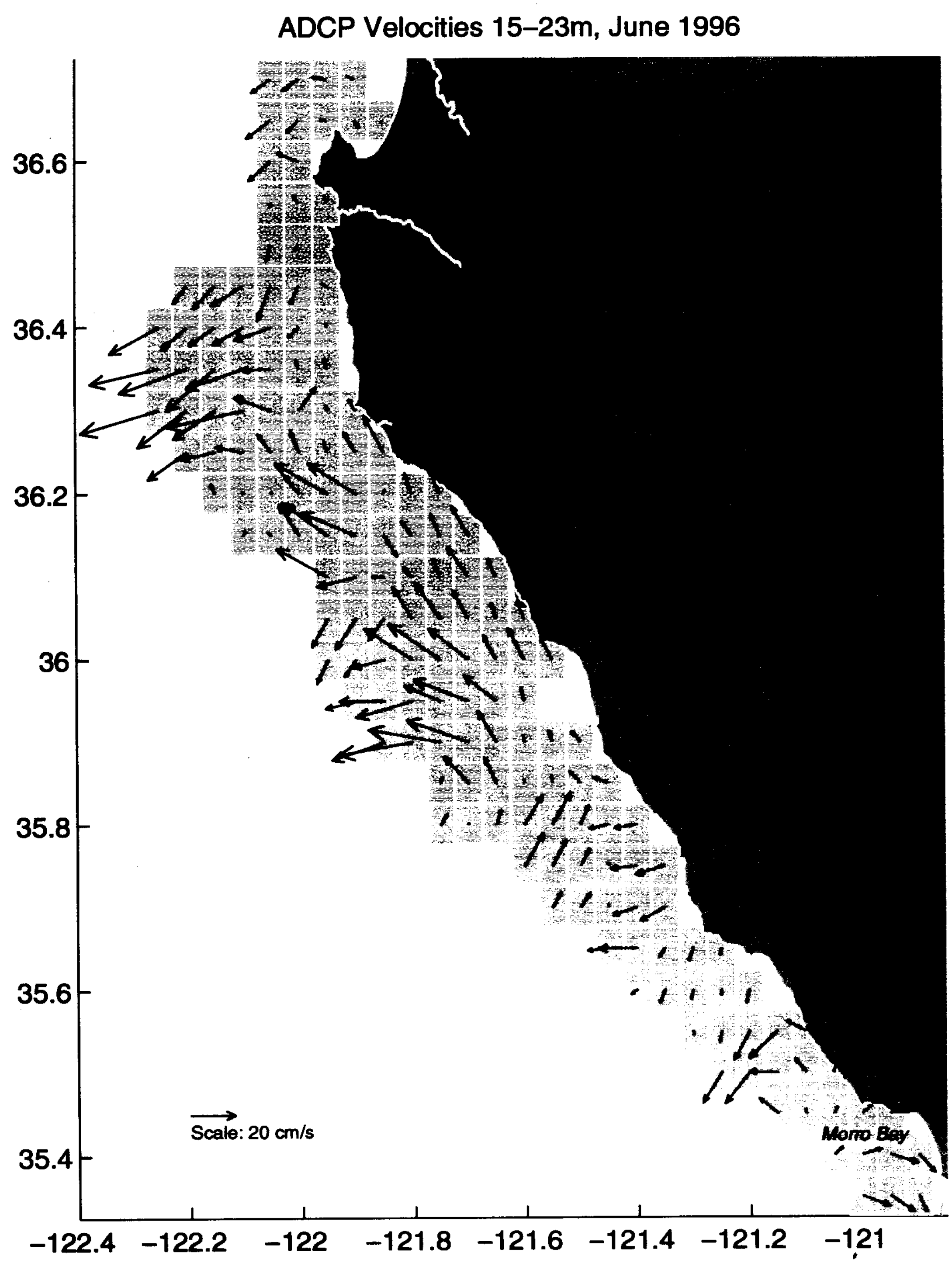

Figure 7a. Horizontal maps of ocean currents (ADCP velocity vectors) from Monterey to Morro Bays, 2-6 June 1996, averaged over 15-23 m water depth. Velocities over a (0.1 x 0.1)-degree region were gridded into 0.05-degree bins. Bins containing data are filled with light gray. The approximate region of the Big Creek Ecological Reserve is indicated with darker fill.

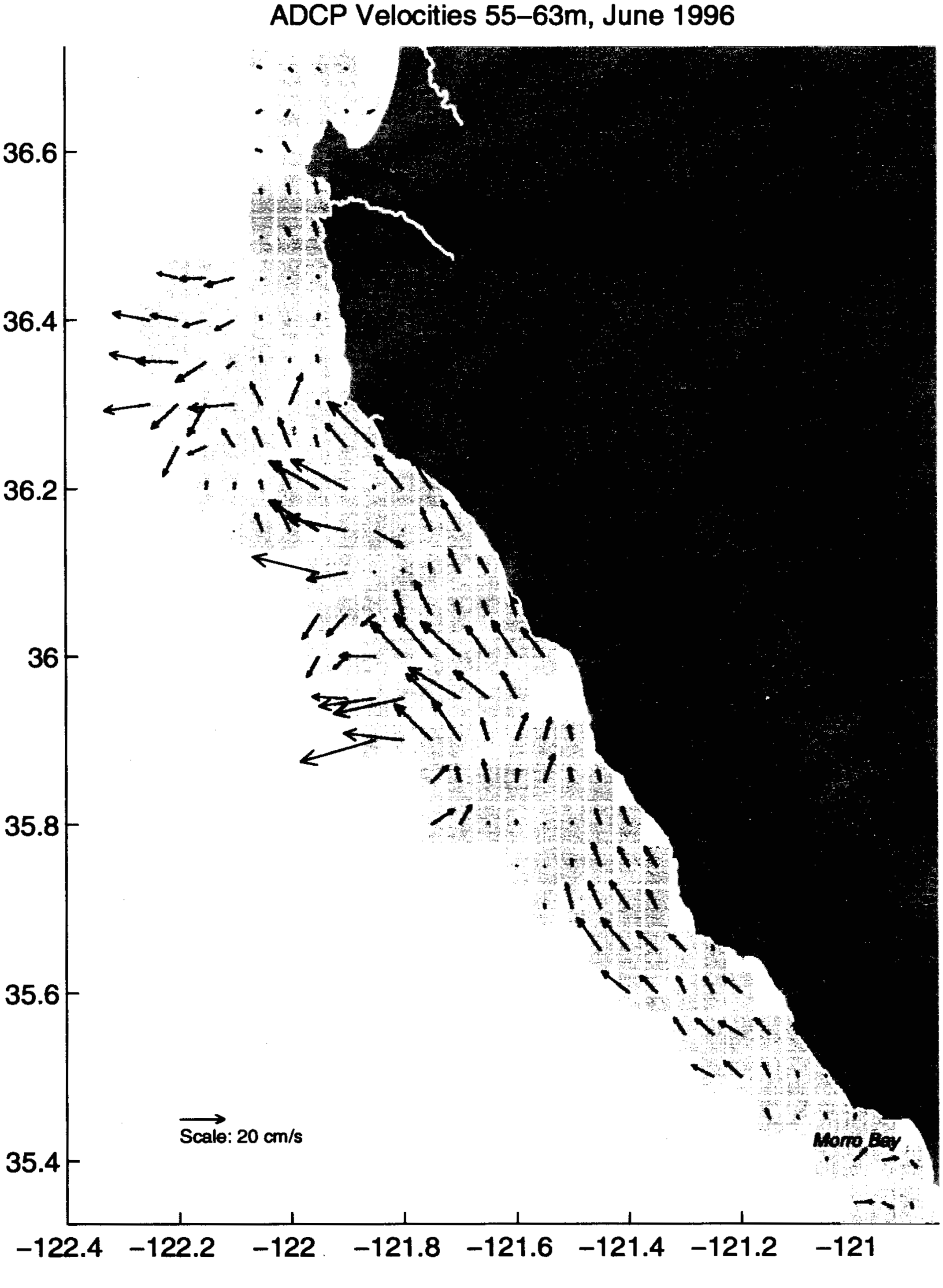

Figure 7b. Horizontal maps of ocean currents (ADCP velocity vectors) from Monterey to Morro Bays, 2-6 June 1996, averaged over 55-63 m water depth. Velocities over a (0.1 x 0.1)-degree region were gridded into 0.05-degree bins. Bins containing data are filled with light gray. The approximate region of the Big Creek Ecological Reserve is indicated with darker fill.

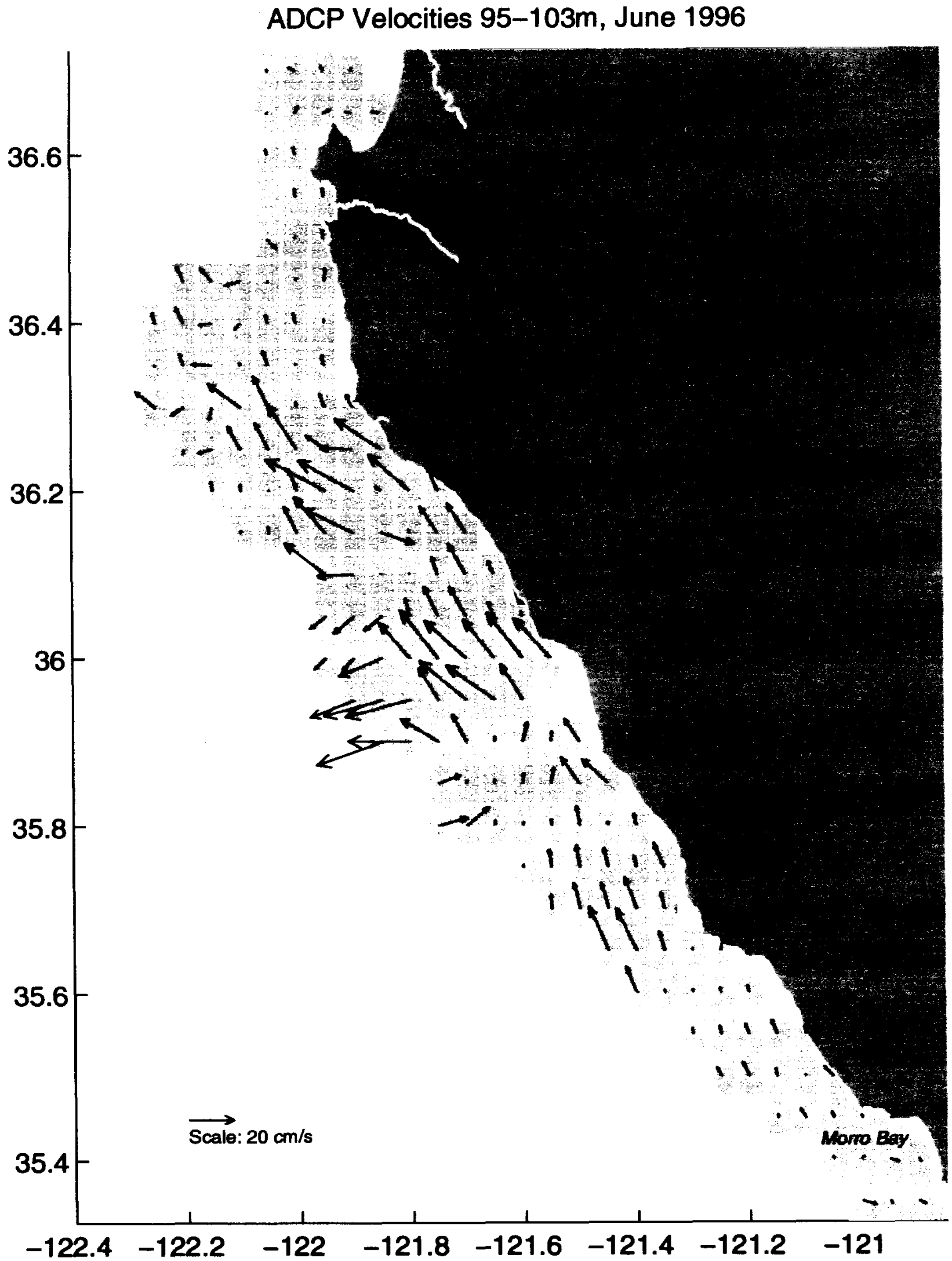

Figure 7c. Horizontal maps of ocean currents (ADCP velocity vectors) from Monterey to Morro Bays, 2-6 June 1996, averaged over 95-103 m water depth. Velocities over a (0.1 x 0.1)-degree region were gridded into 0.05-degree bins. Bins containing data are filled with light gray. The approximate region of the Big Creek Ecological Reserve is indicated with darker fill.

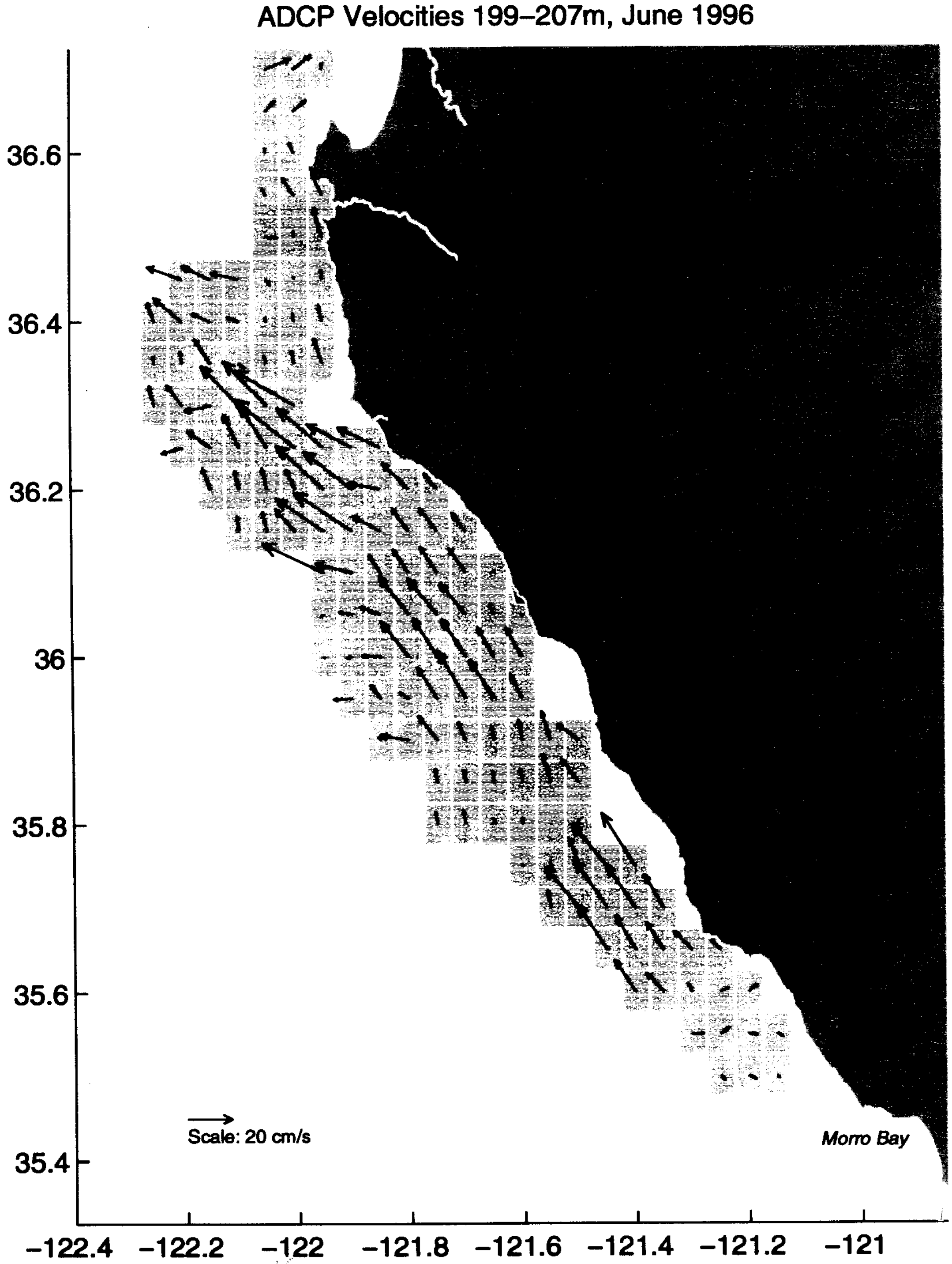

Figure 7d. Horizontal maps of ocean currents (ADCP velocity vectors) from Monterey to Morro Bays, 2-6 June 1996, averaged over 199-207 m water depth. Velocities over a (0.1 x 0.1)-degree region were gridded into 0.05-degree bins. Bins containing data are filled with light gray. The approximate region of the Big Creek Ecological Reserve is indicated with darker fill.

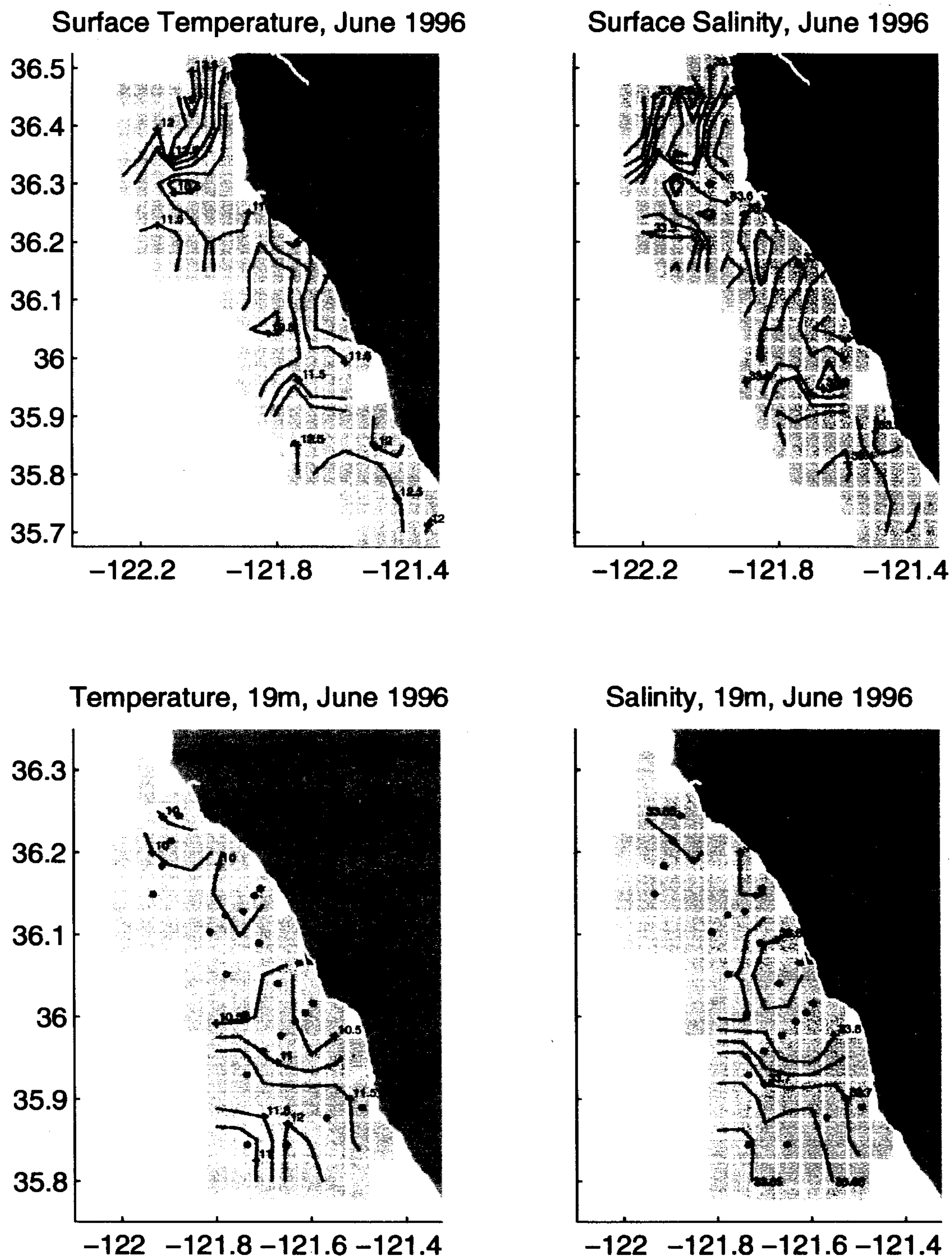

Figure 8. Maps of temperature and salinity measured from Monterey to Morro Bays, 3-6 June 1996. Observations over a (0.1 x 0.1)-degree region were gridded into 0.05-degree bins; bins containing data are filled with light gray. The approximate region of the Big Creek Ecological Reserve is indicated with a darker fill. Contours of temperature are 0.5 °C and of salinity are 0.05 ‰. (a) Surface temperature and (b) surface salinity measured by ship's thermosalinometer. Data were collected every 10 seconds. (c) Temperature and (d) salinity at 19 m depth. Small open circles are positions of CTD stations.

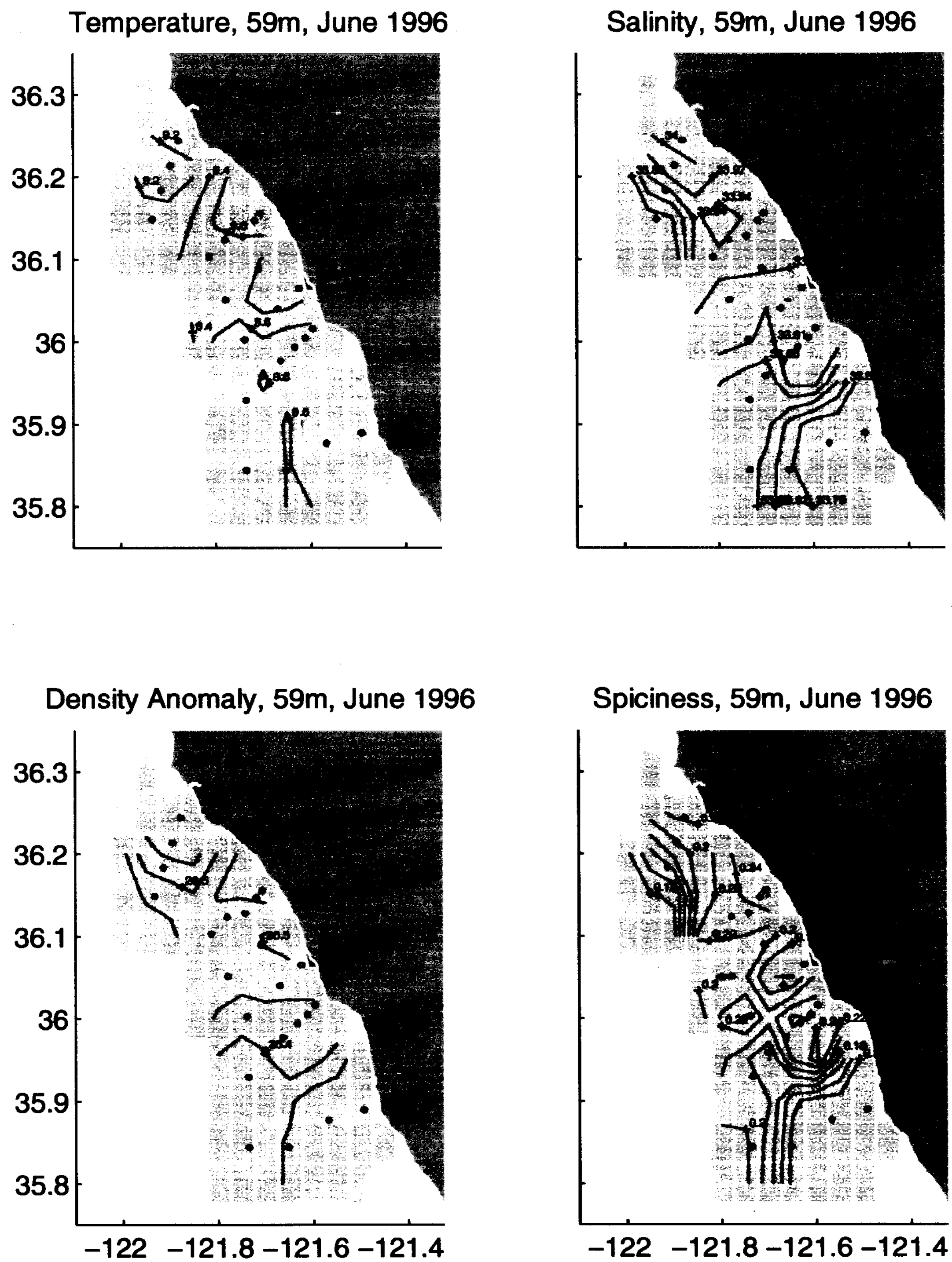

Figure 9. (a) Temperature, (b) salinity, (c) density anomaly, and (d) spiciness[1] measured at 59 m depth. Contour intervals are 0.2°C temperature, 0.03‰ salinity, 0.05 kg/m^3 density anomaly, and 0.02 spiciness. Otherwise, same as Figure 8.

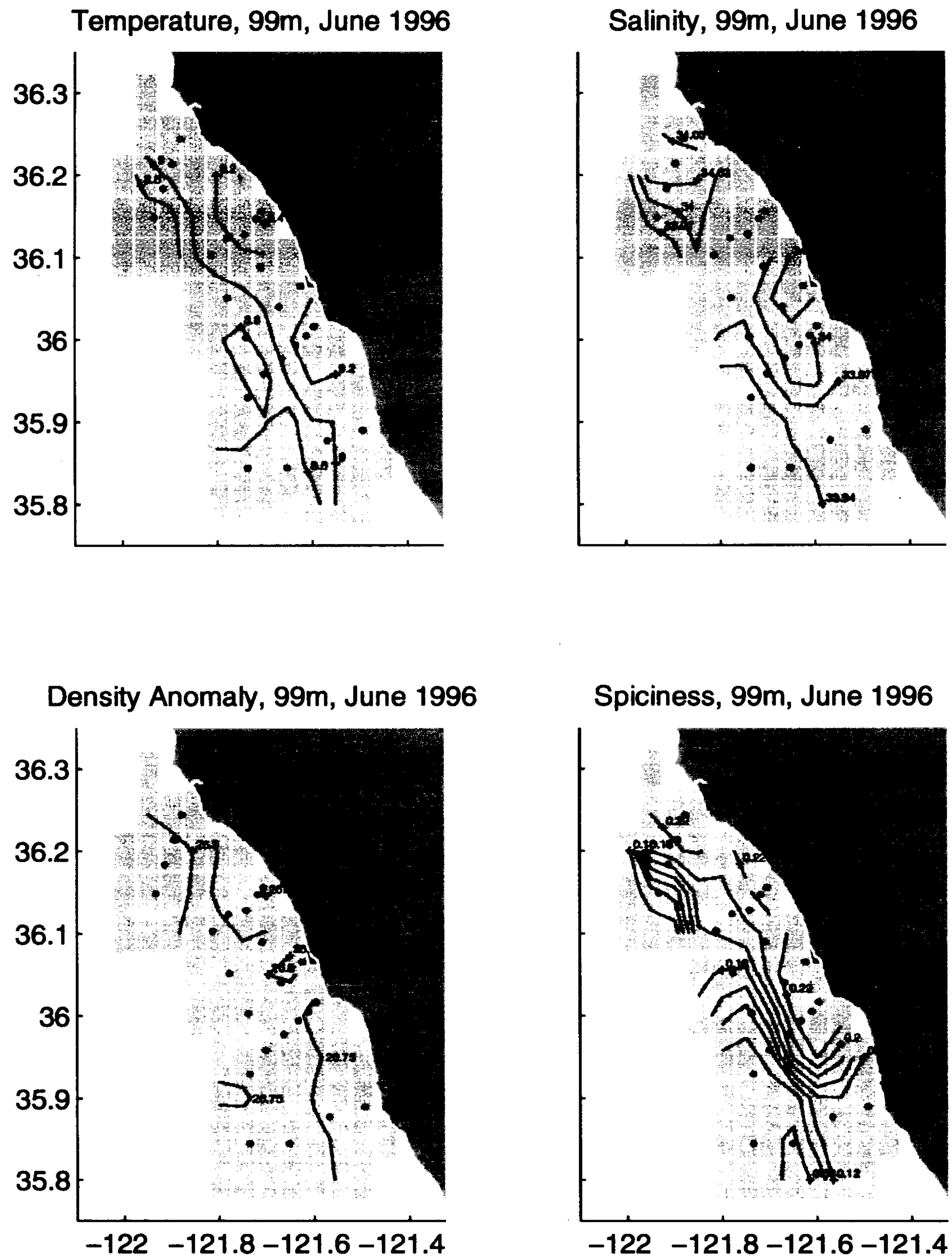

Figure 10. (a) Temperature, (b) salinity, (c) density anomaly, and (d) spiciness[1] measured at 99 m depth. Otherwise, same as Figure 9.

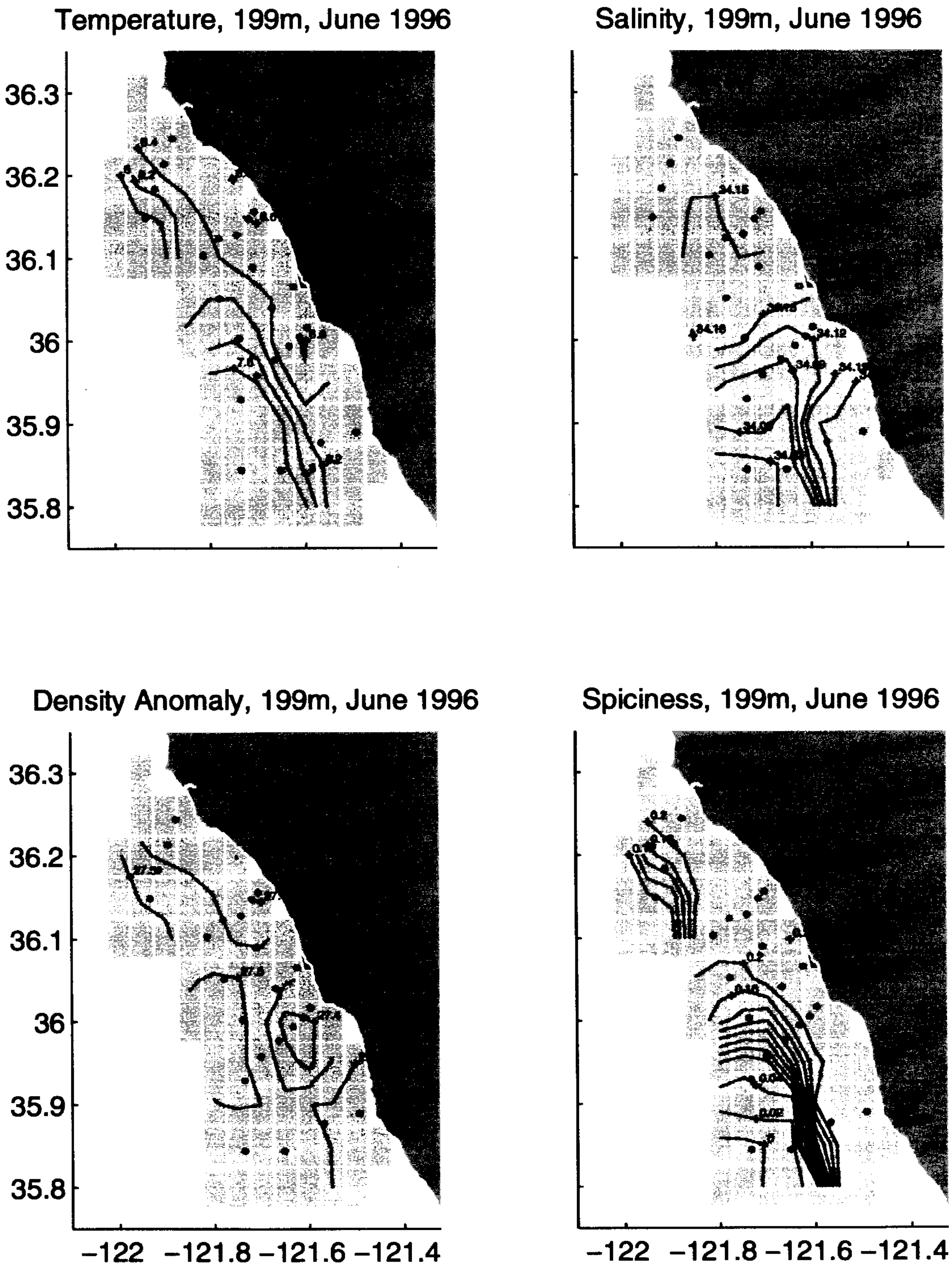

Figure 11. (a) Temperature, (b) salinity, (c) density anomaly, and (d) spiciness[1] measured at 199 m depth. Otherwise, same as Figure 9.

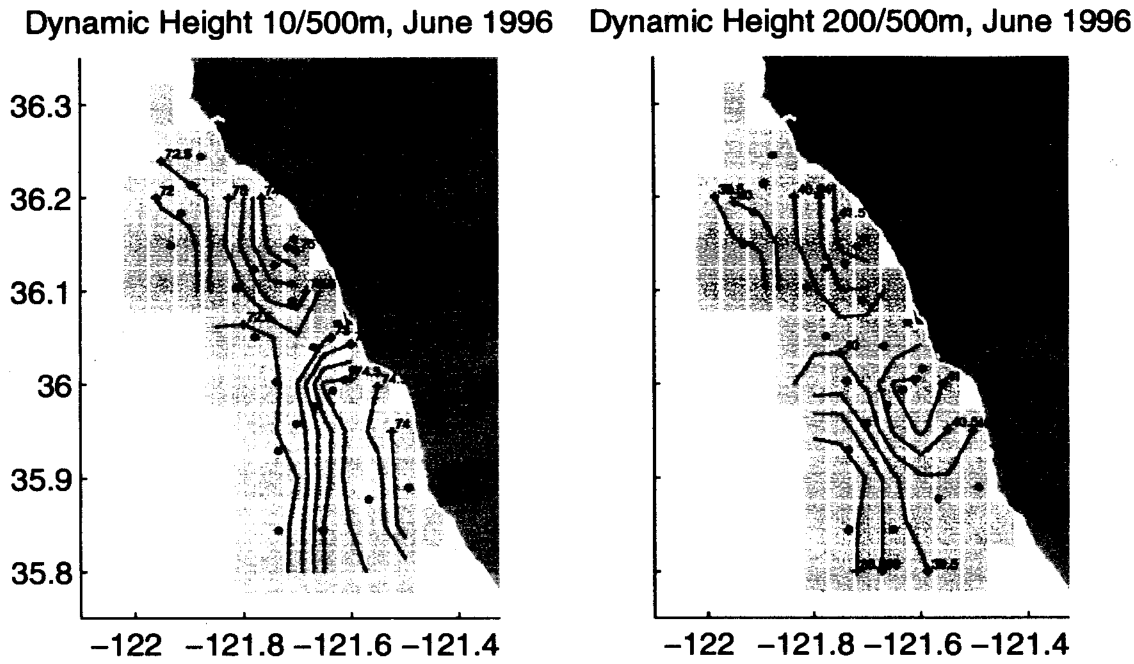

Figure 12. Map of dynamic heights at (a) 10 m relative to 500 m and (b) 200 m relative to 500 m, with contour intervals of 0.5 m. Small open circles are positions of CTD stations.

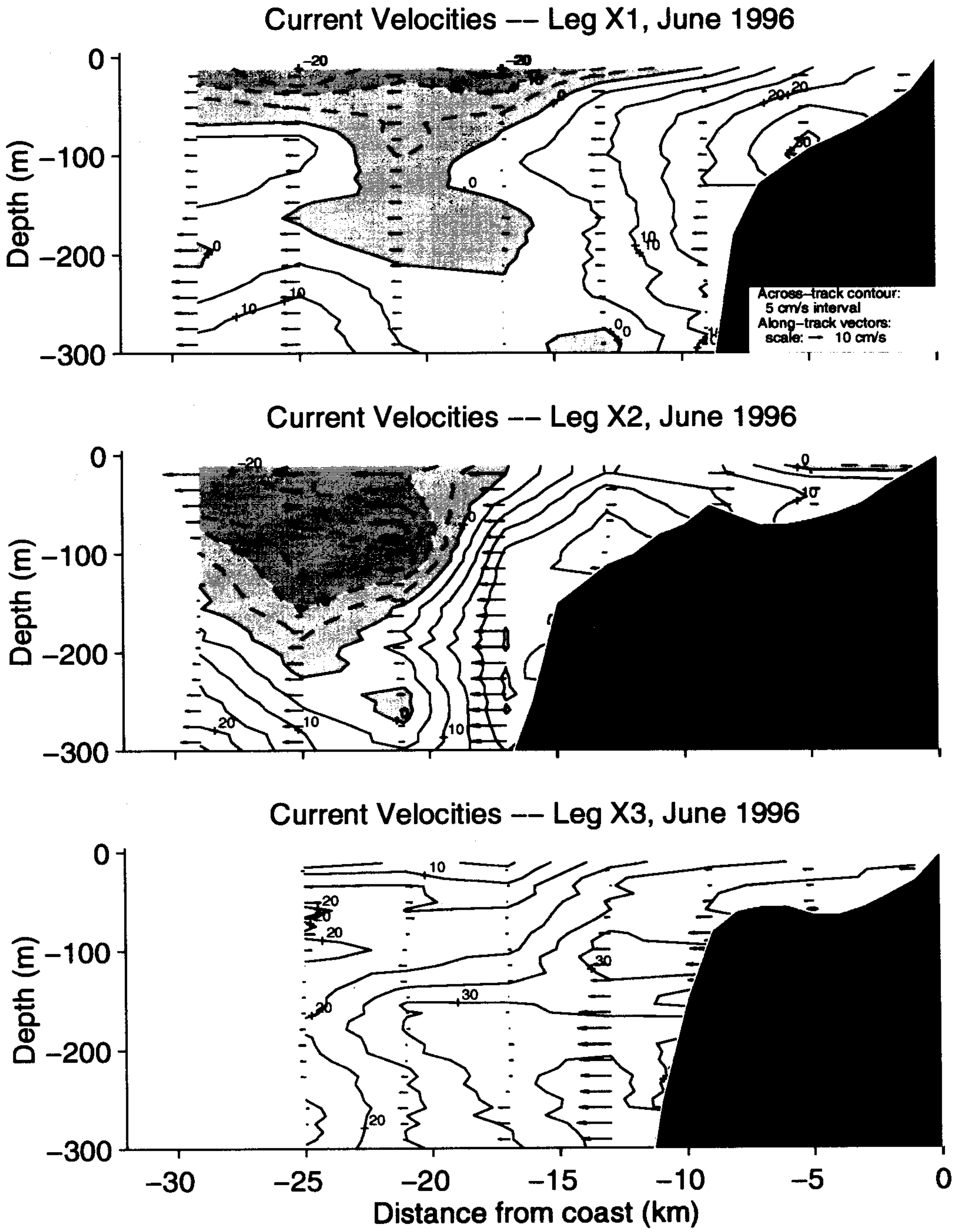

Figure 13. Vertical plots of ADCP current velocities along (a) Leg X1, (b) Leg X2, and (c) Leg X3; locations of legs as indicated in Figure 2a. Along-track and across-track velocities were averaged by depth over a 7-km region and gridded into 4 km x 8 m depth bins. Across-track velocities are contoured every 5 cm/s, and regions of equatorward flow are shaded. Along-track velocities are indicated by horizontal vectors. The continental shelf and slope are filled with black. The compass heading of each leg was (a) 289°, (b) 270°, and (c) 248°.

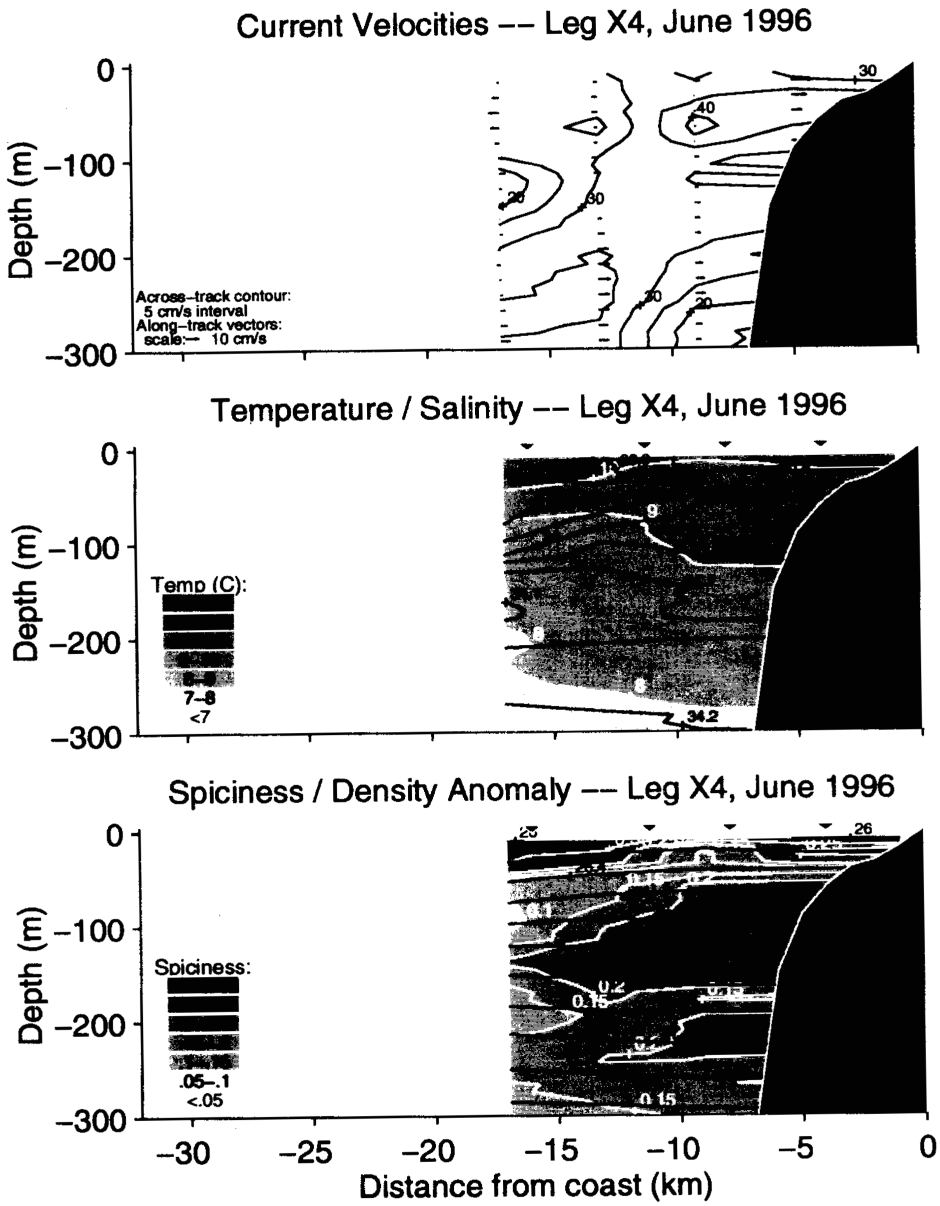

Figure 14. Vertical plots of ADCP current velocities and water mass characteristics along Leg X4; compass heading was 203°. Water mass characteristics from CTD data were averaged by depth over a 7-km region and gridded into 4 km x 8 m depth bins. Locations of CTD stations along each leg are indicated by small black triangles. (a) Current velocities as described in Figure 13. (b) Temperature indicated by shading (see accompanying scale), with white contour intervals of 1°C; salinity indicated by black contour intervals of 0.05‰. (c) Spiciness[1] indicated by shading (see accompanying scale), with white contour intervals every 0.05; density anomaly indicated by black contour intervals every 0.02 kg/m^3.

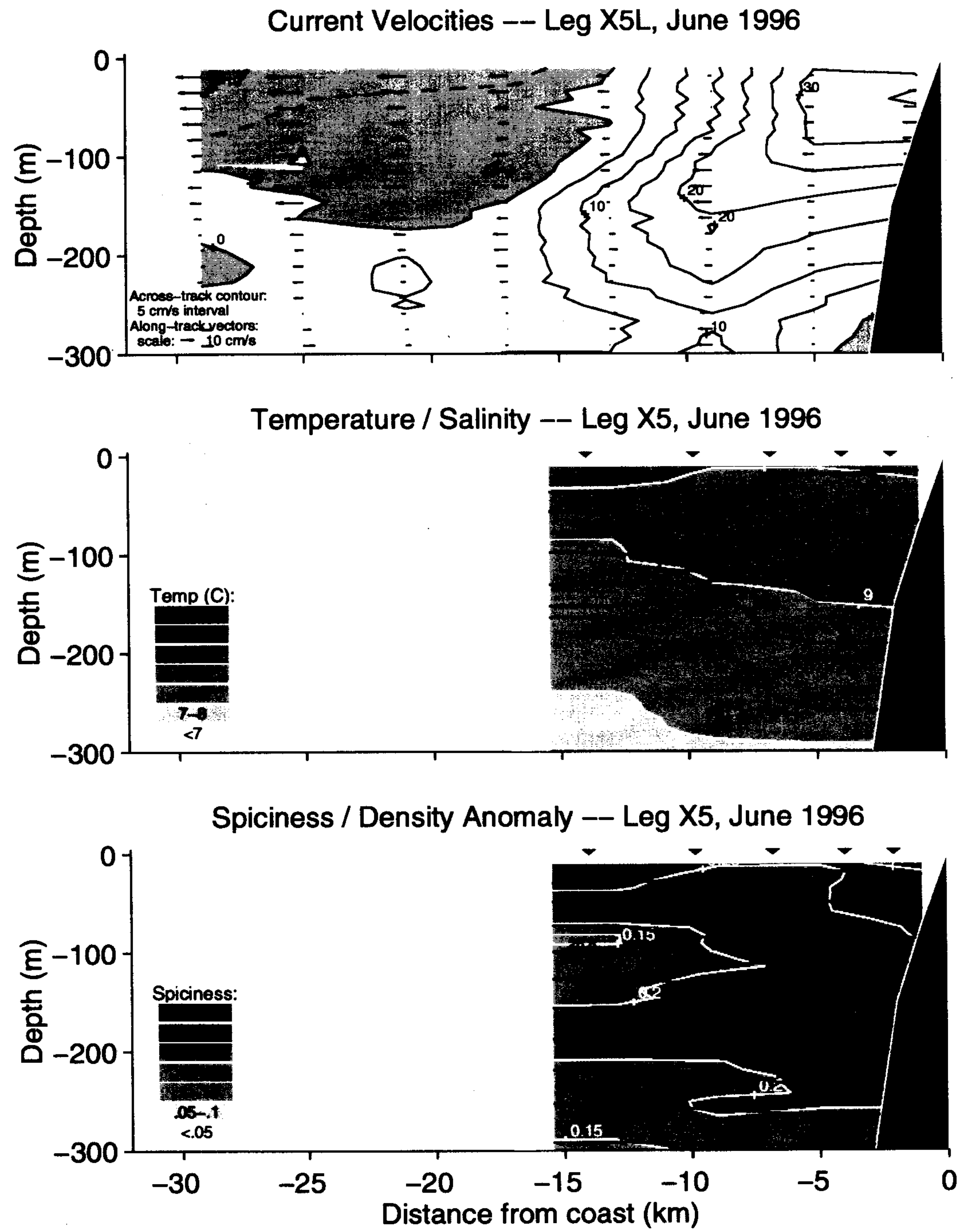

Figure 15. Vertical plots of ADCP current velocities and water mass characteristics along Leg X5; compass heading was 238°. The ship collected CTD along leg X5, then reversed course and steamed a further distance offshore (Leg X5L). Only the ADCP velocities for Leg X5L were included in the gridding. Otherwise, same as Figure 14.

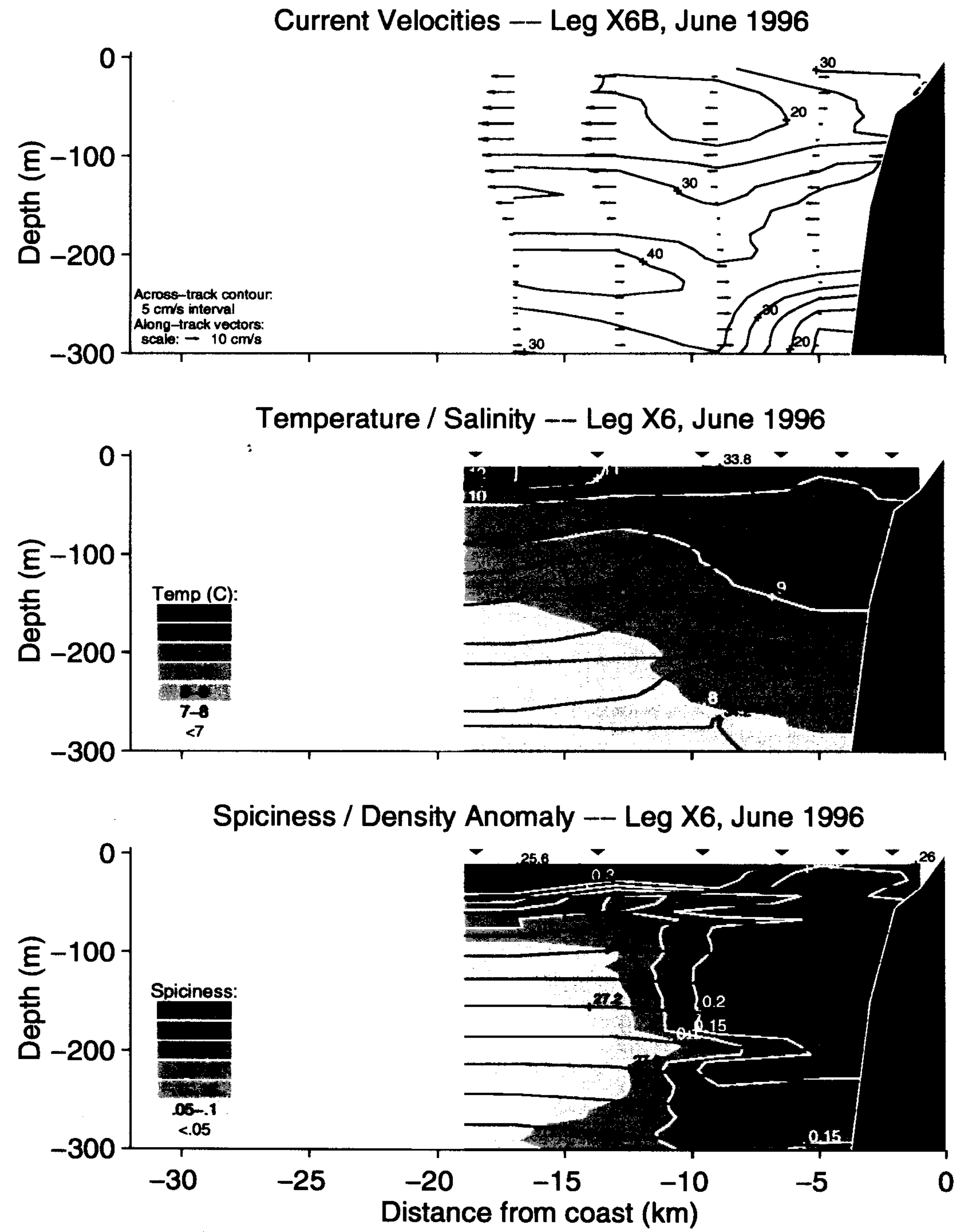

Figure 16. Vertical plots of ADCP current velocities and water mass characteristics along Leg X6; compass heading was 238°. Otherwise, same as Figure 14.

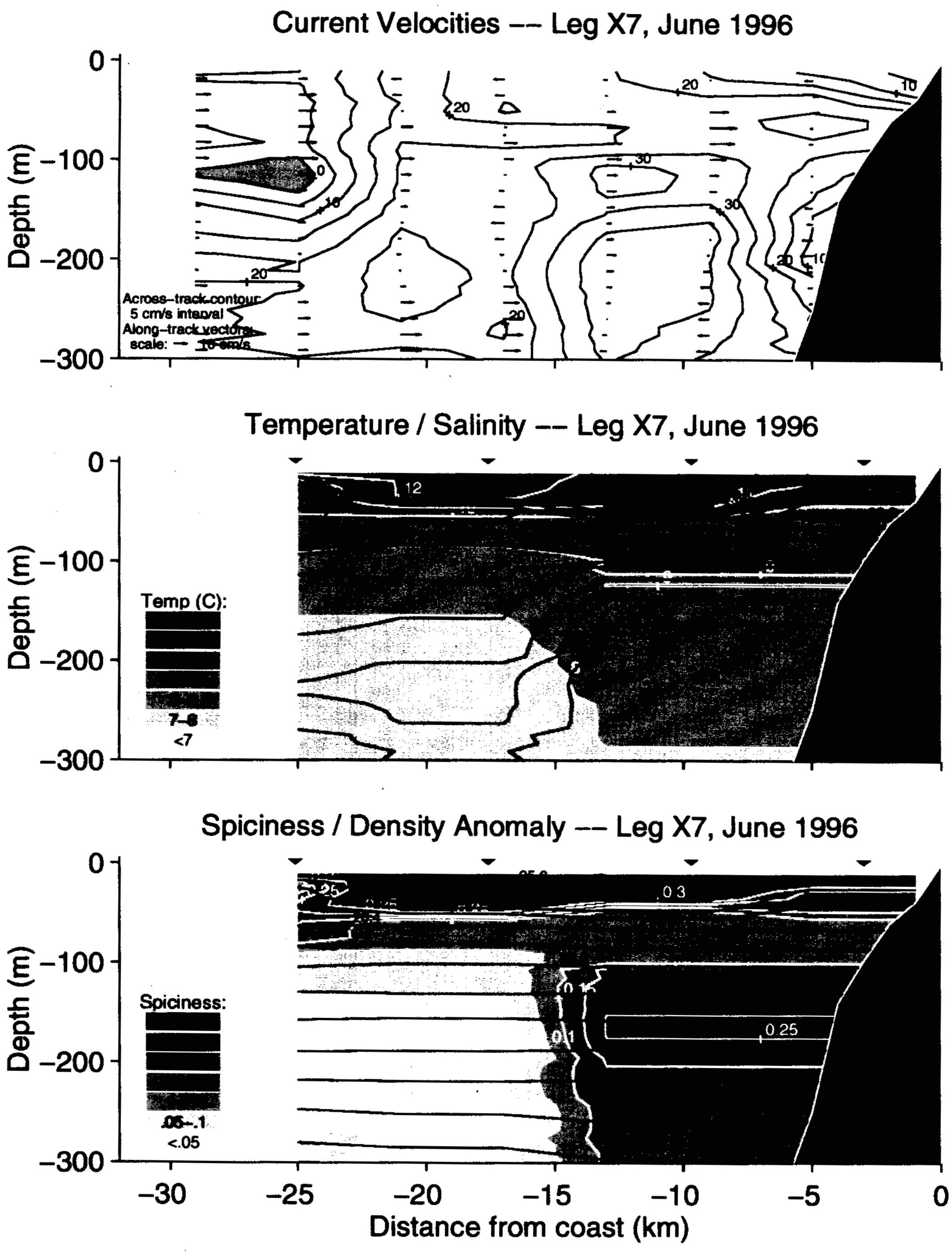

Figure 17. Vertical plots of ADCP current velocities and water mass characteristics along Leg X7; compass heading was 257°. Otherwise, same as Figure 14.

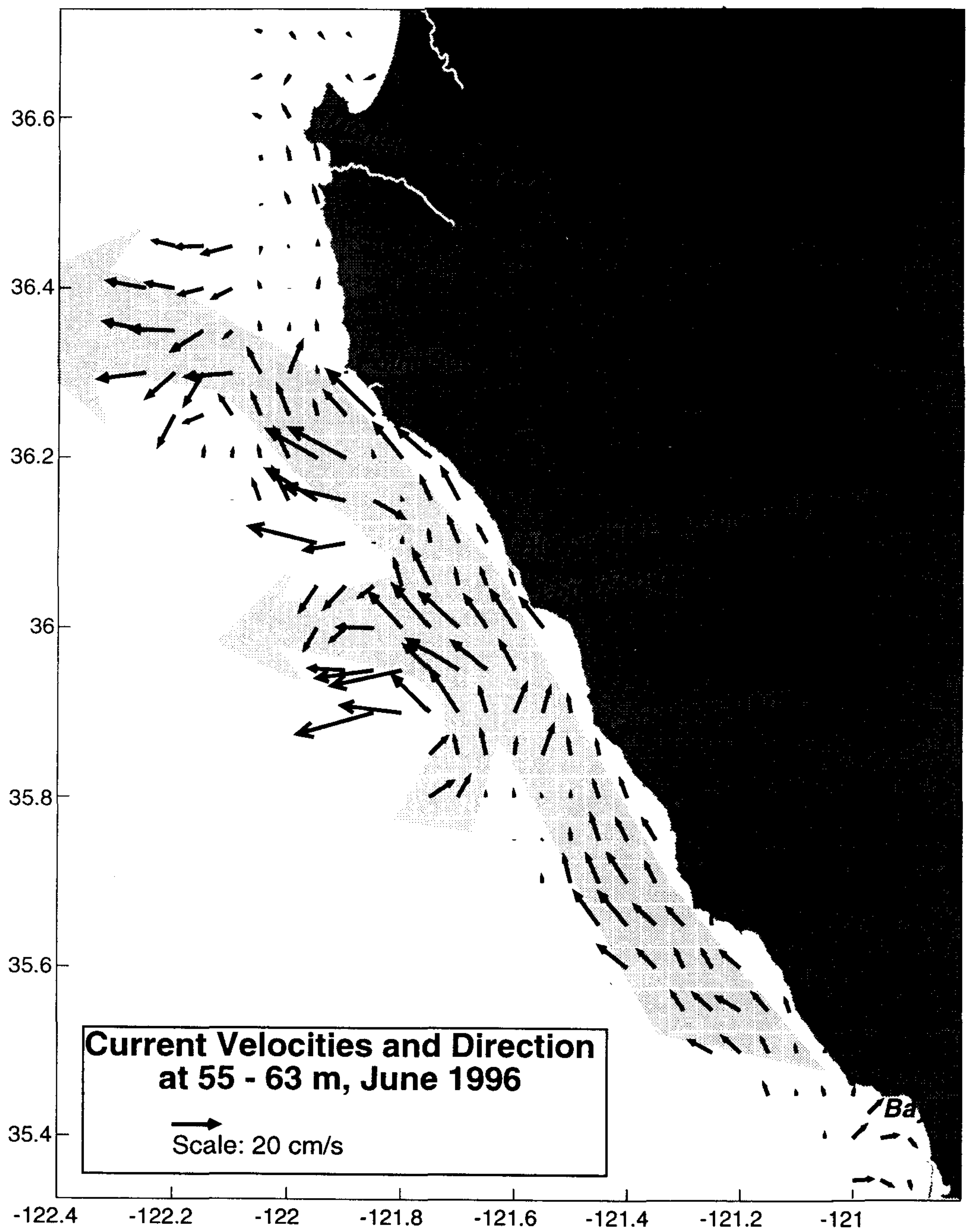

Figure 18. Conceptual model (large gray arrows) of ocean circulation off the Big Sur coast, as derived from current velocity and direction (small black arrows) measured with ADCP on the NOAA ship *McArthur*, 3-6 June 1996.

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