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An Experimental Reef Program to Test Designs of an Artificial Reef for Kelp Mitigation

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An artificial reef is being planned to mitigate alleged losses of giant kelp and the invertebrate and fish communities associated with a kelp bed. The project's first step was to initiate comprehensive siting and design studies. A 25-yr time series of kelp surface canopy maps for a 100 km reach of coastline was entered into a GIS database and analyzed in conjunction with geotechnical and human-use information to define ecologically favorable and acceptable sites in the general area. A site was chosen near an area that appeared most promising in the primary study area. This study's field work determined that the design of the mitigation reef will not be straightforward and that an experimental phase to test various designs needs to be performed. We recommend that a low relief (0.5–1.5 m) reef with relatively high exposure to sand scour and occasional, partial burial be constructed in order to promote the establishment of kelp. Scattered rock and broken concrete at three different density spreads (17, 34, and 67%) on the bottom will be tested. This study has revealed that existing artificial reefs have not typically sustained a persistent kelp bed. This fact, therefore, makes the Phase I experiment even more critical than originally thought.

Southern California kelp beds, dominated by giant kelp *Macrocystis pyrifera,* host hundreds of species of algae and provide habitat for hundreds of species of fish and macroinvertebrates (Limbaugh, 1955; Foster and Schiel, 1985; McPeak et al., 1988; DeMartini and Roberts, 1990). In addition to the habitat the kelp beds provide, kelp contributes substantially to the food chain both directly and by contributing organic material through decomposition processes. Duggins et al. (1989), for example, showed that over half the carbon in certain predatory fish and birds in a kelp-dominated habitat can be traced to carbon ultimately fixed photosynthetically by kelp plants.

The cooling water discharges for the San Onofre Nuclear Generating Station (SONGS) are located just upcoast of the San Onofre kelp bed in northern San Diego county (Fig. 1). These cooling water discharges consist of two diffuser pipes approximately 800 m in length that extend from a water depth of 11–14 m. The San Onofre kelp bed grows on a cobble-boulder reef which rises off the bottom a moderate extent (1 m over an alongshore distance of about 1 km). Sonar studies of this reef area define a hard substrate area of 170 ha that on average supports a 70-ha kelp bed. This average kelp bed size was calculated from down-looking sonar mapping data collected between January 1982 and July 1983. The presence of kelp contributes to a much larger diversity and standing stock of fish than would otherwise occupy this low-relief reef (Quast, 1968; DeMartini and Roberts, 1990).

The operation of the SONGS cooling water system is alleged to have been the cause of adverse effects on the nearshore ecosystem, including the loss of kelp habitat (Bence et al, 1996). The California Coastal Commission permit for SONGS operation requires the owners of SONGS, which include Southern California Edison Company, the San Diego Gas and Electric Company, and the cities of Anaheim and Riverside, to mitigate for this loss of kelp by constructing an artificial reef to replace 60 ha of medium- to high-density kelp (≥ 4 plants/100 m^2). This reef will be constructed in two phases. The first phase will be an experimental reef of approximately 6 ha to test reef designs using different materials and different bottom coverages of these materials. After the successful completion of the experimental reef program, a mitigation reef of an additional 54 ha will be constructed using the material that most cost-effectively meets the goals of maintaining a persistent kelp population and providing suitable habitat for local invertebrate and fish populations.

SITING AND DESIGN STUDIES

The first step in the reef siting and design process was a 2 yr study that addressed the following questions: 1) where, within the constraints of the Coastal Commission permit, is the best ecological location for the kelp bed

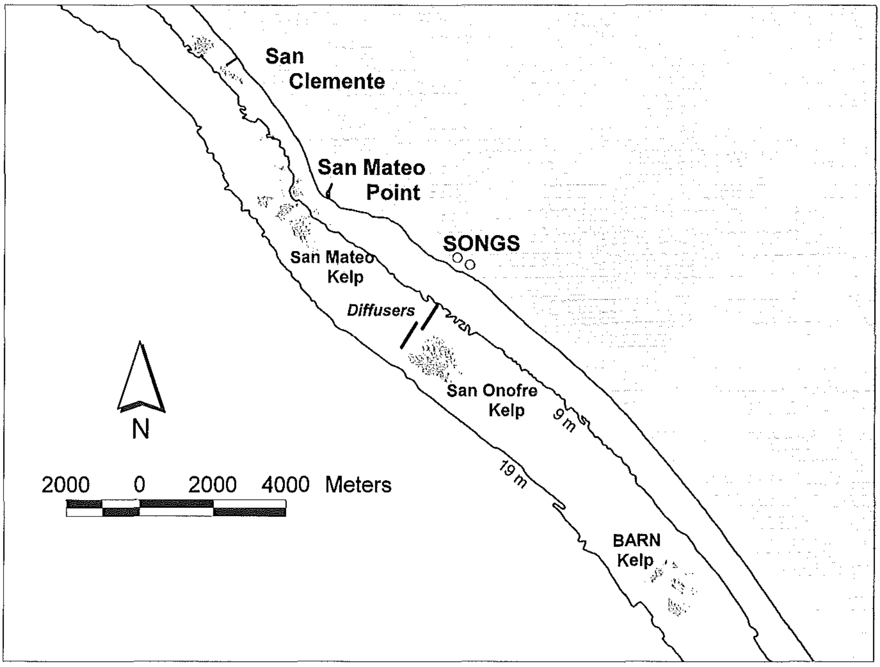

Fig. 1. Relationship of SONGS diffusers and kelp beds in the nearshore region offshore of San Onofre.

reef to be placed; 2) what is the best artificial reef design to support a kelp bed; and 3) what, from a practical engineering viewpoint, is a reasonable approach to this ecologically derived design? The initial study consisted of four elements: field ecology studies, physical monitoring, engineering studies, and geographic information system (GIS) database construction and modeling.

Considerations for constructing the experimental reef covered a wide range of issues including biological constraints relating to the optimum recruitment and growth of kelp, engineering constraints for construction of the reef, and political constraints for placing it within the nearshore coastal zone. Spatial information for all of the siting options and constraints were entered into a GIS database, which was then used to run models to show optimum siting locations and examine the spatial relationships between the different siting and design factors. The GIS database will also be a critical element in determining the exact placement of the experimental reef modules within the general reef site.

The primary biological constraints for siting the reef were that the water depth should be between 12 and 15 m and that the site should be well away from river mouths and others sources of sediment that could potentially settle on the reef substrate and cause high water turbidity. High turbidity levels would reduce light levels below those required for kelp growth and reproduction and would be especially detrimental in the spring when high nutrient conditions are optimal for gamete production in the microscopic stages of the *Macrocystis* life cycle. Gamete production in the microscopic gametophyte is limited to times when threshold conditions of nutrients and light are present (Deysher and Dean, 1986). In addition, siting the reef adjacent to persistent populations of *Macrocystis* will provide a natural source of propagules for recruitment of kelp and other kelp bed algae and invertebrates. However, the reef cannot impinge on nearshore populations of special interest, such as sand dollar beds.

The basic design of the artificial reef modules is to have scattered rock or concrete in a single layer over the bottom. This appears to be the ideal configuration for the establishment of persistent kelp populations, as discussed later in the design studies. However, there was great concern among the engineers that scattered rocks or concrete placed on sand would quickly sink below the surface and disappear. Therefore, nearshore areas with a thin veneer of sand (<0.3 m) were deemed optimal for construction of the reef, and areas with between 0.3 and 0.5 m of sand were deemed to be acceptable. Preliminary sonar

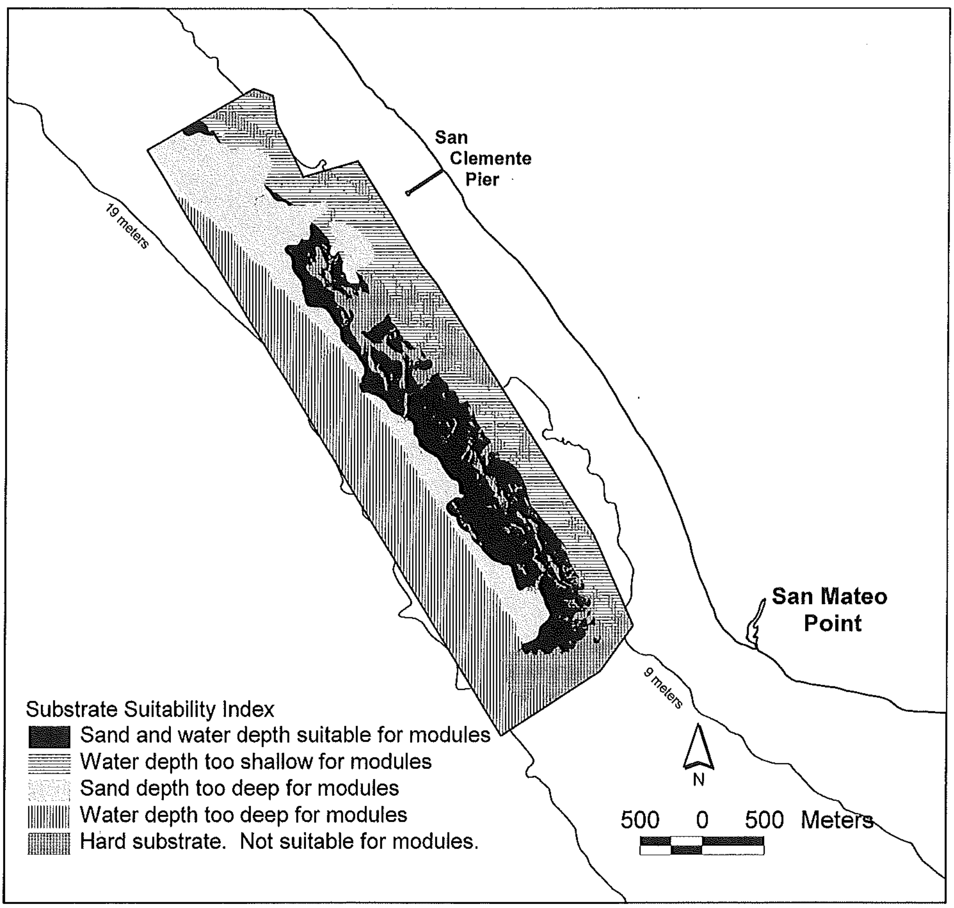

Fig. 2. Region offshore of San Clemente selected for the experimental reef project. The suitability of sediment and water depth characteristics for the experimental reef modules is also shown.

studies were conducted in 1992 (Eco-M, 1993) to provide a general overview of sand depths in the region. High-resolution sonar studies were conducted in 1997 over the highest priority sites to provide greater detail for the exact placement of the experimental reef modules.

The nearshore coastal zone in southern California is a finite and valued resource and there were many political concerns about the siting of a large artificial reef. One of the biggest constraints in locating an appropriate reef site was in minimizing conflicts with the amphibious training zone designated by the Marine Corps offshore of Camp Pendleton in northern San Diego County. This area is just south of SONGS and it is an ideal location for the reef because it was in close proximity to the affected resource. However, the Marine Corps had very strong concerns about the artificial reef interfering with amphibious training exercises. Other political interests taken into account included recreational boaters who did not want the reef placed in local sailboat racecourses near the Dana Point and Oceanside harbors. Archaeological and shipwreck sites were also considered, but none were identified in the areas under highest consideration for reef placement. The local sport and commercial fishers viewed the reef as a positive resource and were supportive of the reef siting process.

The analysis of all these factors in the GIS siting model led to the selection of an optimal reef site just north of San Mateo Point in the southern San Clemente region (Fig. 2). This reef site had a large area where there was a thin layer of sand overlying rock or other hard substrate within a depth range suitable for kelp; had temperature, light, and wave regimes that appeared suitable for kelp; and was in close proximity to persistent kelp beds. Sites

TABLE 1. Summary of information on southern California artificial quarry rock reefs.

Reef	Year built	Reef size (ha)	Substantial kelp last observed	Sea fans first observed	Sea fans dominant or abundant	Kelp condition	Kelp density > 4 plants/100 m²
Torrey Pines	1975	0.4	1976–1977	1977	1986	none	no
Pendleton	1980	1.4	never	1982	1984	few plants on fringe	no
Pitas Point	1984	0.4	1986–1987	1987	?	buried, no kelp	no
Oceanside	1987	1.5	1990–1992	1990	1993	none	no
Pacific Beach	1987	1.6	1990–1992	none[a]	no	few plants on fringe	no
Carlsbad	1990	1.6	1992–1993	none[a]	no	abundant	yes[b]

[a] These reefs may not be old enough for the development of sea fan populations.
[b] Qualitative surveys in 1993 suggest that kelp density probably exceeded 4 plants/100 m². However, it is uncertain whether this density will persist as the reef matures.

off Camp Pendleton (to the south of SONGS) and at Carlsbad had comparable physical characteristics, but were rejected because of interference with Marine operations (Pendleton) or because of the uncertainties of the effects of nearby wetland restoration and beach replenishment projects scheduled for Carlsbad and other north San Diego county locations.

The design portion of the initial study involved ecological and geologic field studies, engineering studies, and a review of available data on natural kelp and artificial reefs in southern California. These studies revealed that existing artificial reefs, most of which are relatively high-relief piles of quarry rock, did not support persistent kelp populations and were often dominated by sessile invertebrates (Table 1). High densities of kelp were observed on some reefs, but these were present only within the first several years of construction, before the reefs became dominated by sessile invertebrates. The few kelp plants observed on older artificial reefs appeared more frequently at the edges than on the slopes and crests of these rock-pile structures. Further evidence suggests that dense populations of sessile long-lived invertebrates (i.e., sea fans) can outcompete kelp. Furthermore, field investigations indicated that most natural kelp plants were generally attached to lower relief reefs than the artificial reefs. Those natural reefs that supported persistent kelp populations were generally low to moderate relief with a moderate amount of sand interspersed among the hard bottom substrate. Very low-relief reefs, with a very high proportion of the substrate covered with sand, did not support persistent stands of kelp. These observations led to the working hypothesis that the development of kelp populations requires moderate levels of sand scouring in order to inhibit colonization by sessile invertebrates, but not so frequently as to preclude colonization by kelp. The conclusion of these design studies was that a successful kelp reef design would be a relatively low-relief profile, with a moderate proportion of sand–rock interface that would provide intermediate levels of scouring.

Engineering studies indicated that single rocks placed on thick layers of sand would soon become buried. There are alternative ways of insuring that rocks will not become buried, including the placement of a gravel or filter fabric base prior to placement of reef rock. However, these alternatives are costly. The potential for rock burial can be alleviated somewhat by placing the reefs in areas where the sand layer is thin. The placement of rock on thin veneers of sand will be the primary approach in this artificial reef program.

THE ARTIFICIAL REEF FOR KELP—A DESIGN EXPERIMENT

Although the initial siting and design studies described above resulted in a narrower focus for building the 60-ha mitigation reef, they did not provide sufficient information to develop a specific design plan that would be certain to support persistent kelp populations. As a result of the remaining uncertainties with respect to reef design, an experimental reef plan with several alternative reef designs was proposed to be tested.

The experimental reef will use both quarry rock and recycled concrete as the material for constructing the different reef modules. There is a long history of artificial reef construction using quarry rock. It is readily available and has proven to be an environmentally acceptable material for use in reef construction. However, a recently constructed concrete reef off of Mission Beach in San Diego has shown promise as a kelp habitat, and this material will also be tested for use in building a kelp reef (D. Bedford, pers. comm.).

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TABLE 2. Proposed coverage for three reef designs based on quarry rock.

Design	Rock/hectare (metric tons)	Cover of substrate (% rock)	Approximate number of boulders (> 30 cm) per 100 m²
Scattered rock low density (SRLD)	3,186	17	22
Scattered rock medium density (SRMD)	6,372	34	44
Scattered rock high density (SRHD)	12,744	67	88

The experimental reef plan will evaluate several different designs to determine which of these will provide suitable kelp habitat. This study will focus on the following questions. 1) What percentage of rock cover will support medium- to high-density giant kelp and an associated kelp forest biota that is similar in cover and density to natural reefs within the region? 2) What size rock will perform best in a reef design where rocks are placed in a monolayer over a thin (approximately 30 cm) veneer of sand? 3) Is there a significant difference between reefs composed of recycled concrete and those composed of quarry rock? 4) Do reefs that are isolated (i.e., ≥2 km away from a large kelp population) perform as well as those that are adjacent to persistent kelp populations?

The experimental reef plan calls for the placement of six types of moderate- to low-relief reefs, three of which will be constructed of quarry rock and three of recycled concrete material. All of the designs are to be placed on thin layers of sand and will consist of scattered rock or concrete that will cover 17, 34, and 67% of the bottom, respectively. The highest cover of rock will use 12,744 metric tons/ha to provide 67% coverage (Table 2). This rock will be normal quarry stone with primarily 30-cm stones and 60-cm boulders, with some 1-m boulders seeded into the mixture. Table 3 summarizes the weights of different size rocks from two quarries on Catalina Island. Coverage is calculated assuming a 1-m boulder has a cross-sectional area of 0.89 m^2 (average of cross-sectional areas of a 1-m cube and a 1-m sphere), a 60-cm boulder has a cross-sectional area of 0.32 m^2, and a 30-cm stone has a cross-sectional area of 0.08 m^2. The 67% coverage figure can be achieved using 21 boulders/100 m^2 in the 75–125 cm size range, 67 boulders/100 m^2 in the 50–75 cm size range, and 336 stones/100 m^2 sized 15–50 cm. Tonnage is based on rock that has a specific density of approximately 2.7 from the Pebbly Beach quarry on Catalina Island.

TABLE 3. Weight of rock from the two quarries on Catalina Island.

Rock diameter (cm)	Pebbly Beach quarry weight (kg)	Empire quarry weight (kg)
30	75	67
60	600	536
100	2,020	1,810
130	4,535	4,264
160	9,344	8,346
200	16,150	14,515

Studies on the survival of young *Macrocystis* sporophytes by Dean (1985) showed that survival rates were highest on boulders greater than 30 cm in size. The habitat for giant kelp, therefore, appears to be defined, in part, by this size of substrate. The 67% design of quarry rock cover, with over 88 rocks greater than 30 cm in diameter per 100 m^2, provides 20 times the number of attachment sites necessary to support a kelp density of 4 plants/100 m^2. This kelp density is a common index used to portray a viable kelp bed. The 34% cover design with 6,372 metric tons of rock per hectare will provide approximately 44 boulders/100 m^2. The lowest cover of 17% will provide approximately 22 boulders/100 m^2.

The recycled concrete material has a lower specific gravity than the Pebbly Beach quarry rock, 2.2 (Oberg et al. 1984) versus 2.7, and therefore, the same tonnage of material will cover more area. Assuming that the average piece of concrete will be 0.6 × 0.9 × 0.15 m, then approximately 2,914 metric tons of material per hectare will be required for the 67% coverage, 1,457 metric tons per hectare for the 34% coverage, and 729 metric tons per hectare for the 17% coverage (Table 4.) This recycled concrete will most likely be "curb and gutter" material from construction projects, which is generally 15 cm thick with no rebar. If the material is thinner than 15 cm, tonnages may be less than that estimated above.

Seven treatment blocks containing one module of each treatment (unique combinations of low-, medium-, and high-density scattered rock and recycled concrete designs; Table 5) will be placed in the experimental reef site located

TABLE 4. Proposed coverage for three reef designs based on recycled concrete.

Design	Material/hectare (metric tons)[a]	Cover of substrate
Recycled concrete low density (RCLD)	729	17%
Recycled concrete medium density (RCMD)	1,457	34%
Recycled concrete high density (RCHD)	2,914	67%

[a] This estimate is based on an estimated average size for concrete of 0.6 × 0.9 × 0.15 m and the average ratio between the specific density of concrete and Pebbly Beach quarry rock. Differences in the composition of the recycled concrete, both in size of the material and density, may cause the amount of material required to produce the desired coverage to vary from this estimate.

offshore of San Clemente between the San Mateo kelp bed and San Mateo Rocks (Fig. 3). The size of the reef site was chosen to provide for sufficient area to build out both phases (experimental and final build-out) of the mitigation reef. The blocks within the area where the modules are to be placed will be laid out at varying distances from the San Mateo kelp bed. This design will help to insure that modules are near the source of kelp spores at San Mateo kelp, yet provide for the complete coverage of the potential area for the final mitigation reef. Figure 3 shows a potential design in which the blocks are arranged at successively greater distances from the San Mateo kelp bed. This design clusters most of the modules nearer the kelp bed, which will help offset any potential effect of distance from natural kelp beds on the recruitment and survival of kelp on the artificial reefs. Other potential designs include equal spacing of the module blocks to better test the suitability of the entire reef site for the construction of the final mitigation reef.

Modules will be placed within a depth range of 12–14.5 m and will be spaced as evenly as possible within each block. Areas of hard substrate will be avoided. Treatments will be randomly assigned to modules within blocks. Module treatments will be reassigned if there are apparent biases in their placement with respect to depth, proximity to the San Mateo kelp bed, or proximity to naturally occurring reef outcrops.

Each module of the six reef designs will measure approximately 40 by 40 m and will be the same shape and configuration to facilitate comparisons between the reef types. We envision that the modules will be roughly trapezoidal in shape with an area of 0.16 ha. A major factor in determining the final shape of the modules will be the logistics of off-loading the rocks and concrete from the barges in a manner that is both cost effective and capable of being replicated from module to module. The exact reef shape and distribution of substrate will be finalized in discussions with the construction contractors.

Within the defined reef site offshore of San Clemente, the exact placement of each reef module will be determined by a series of diver surveys. Preliminary surveys have been conducted to verify the sand thicknesses identified in the high-resolution sonar mapping studies and to characterize the biological communities. Survey sites were located by selecting coordinates for the southwest corner of each potential module site from the geotechnical data maps in the GIS database. Diver surveys were then conducted on 30-m long transects extending east from this location and at a site approximately 30 m north of this location (Fig. 4). The divers noted all epibenthic invertebrates, algae, and fish within 1 m of each side of the transect and determined the sand thickness at 5-m intervals along the transect. Sand thickness was determined with a 1-m long steel rod (1 cm thick) to a resolution of 10 cm.

The invertebrate communities on the sand substrates surveyed to date have consisted pri-

TABLE 5. Technical specifications for quarry rock reef designs.

	Low density	Medium density	High density
Rock size (range, cm)	15–125	15–125	15–125
Rock size (mean, cm)	50–75	50–75	50–75
Coverage by rock (%)	> 17	> 34	> 67
Rock distribution	dispersed	dispersed	dispersed
Reef height (maximum, m)	1.25	1.25	1.25
Reef height (avg. max. m/100 m^2)	0.5–1	0.5–1	0.5–1

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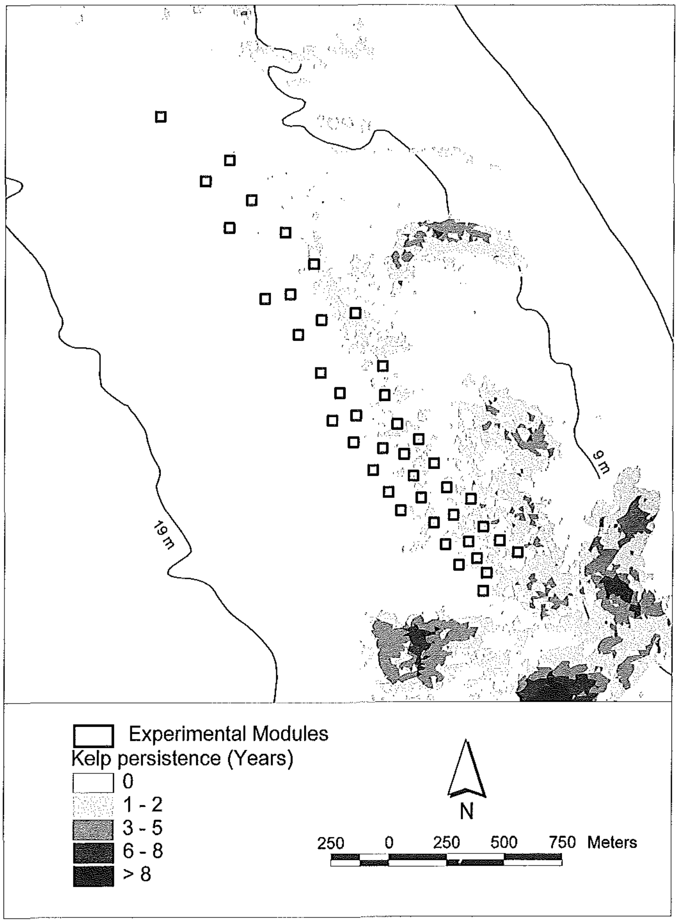

Fig. 3. Positions of the experimental reef modules in relation to kelp persistence (years of kelp presence in period from 1967 to 1994).

marily of the tube-building polycheate *Diopatra ornata* (maximum density 10/m^2) and scattered individuals of the sea pansy, *Renilla kollikeri*; the seapen, *Stylatula elongata*; the seastar, *Astropecten armatus*; and the snails *Kelletia kelletti* and *Olivella* spp. Individuals of the nudibranch *Flabellinopsis iodinea*; the brachyuran crabs *Loxorhynchus* spp. and *Randallia ornata*; the seastar, *Patiria miniata*, and the heart urchin, *Lovenia cordiformis*, were also noted. No individuals of the sand dollar, *Dendraster excentricus*, or the urchin *Lytechinus anamesus* were noted on any of the transects. Organisms on the scattered boulders noted in the surveys included the red algae *Acrosorium uncinatum*, *Gigartina* spp., and *Gelidium* spp. and the brown algae *Desmarestia* spp., *Laminaria farlowii*, *Pterygophora californica*, *Macrocystis pyrifera*, and *Cystoseira osmundacea*. Invertebrates on these hard substrates included sea fans, *Muricea* spp., and various bryozoans, tunicates, and sponges.

After the experimental reef modules are built, postconstruction surveys will be conducted for three purposes: 1) To insure that the reefs were built to specifications, documenting the module shapes, locations, and substrate coverage; 2) as a baseline to assess each reef design with respect to their persistent physical attributes and how their substrate characteristics change over time; and 3) as a baseline to compare designs with respect to biological communities that colonize the reef.

A survey of the physical characteristics of the reef will be completed immediately after construction, as weather permits. This will consist of a side-scan sonar survey of substrate distribution at the site and a diver survey to examine finer scale bathymetric and substrate features. The surveys will be conducted using GPS navigation and underwater acoustic positioning so that maps can be produced that have horizontal positioning accurate to 2 m or less.

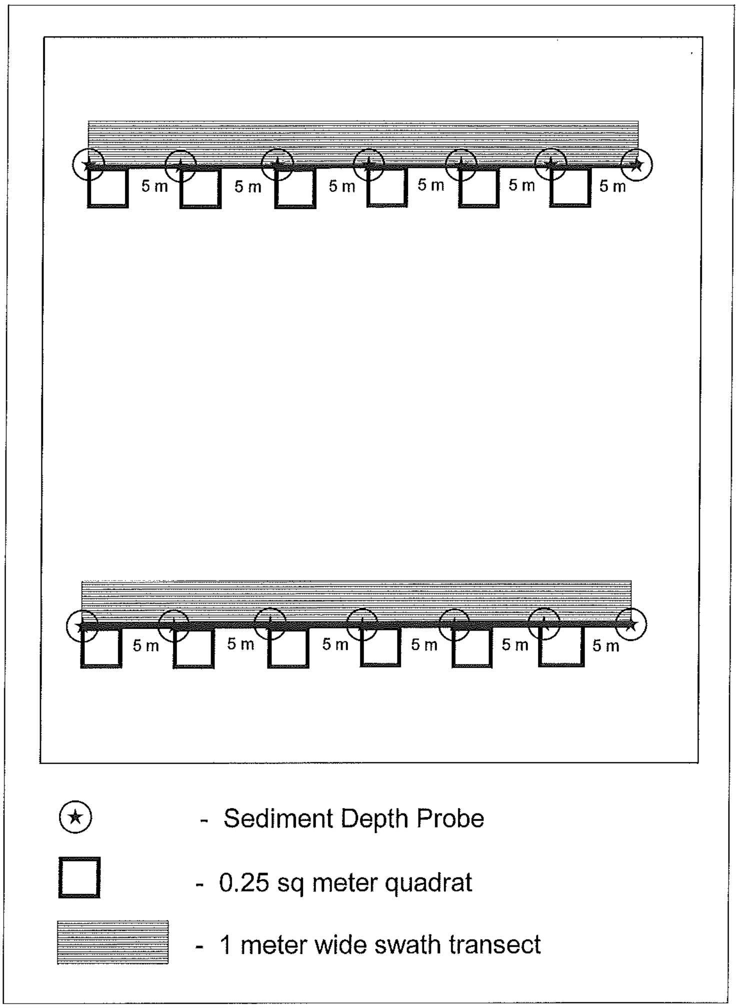

Fig. 4. Schematic of diver survey transects within each of the planned experimental reef modules.

Diver surveys will document the substrate type and the height of the substrate above the sea floor. In addition, organisms on the transects will be documented with diver counts and video recordings. The position of each transect will be marked for future observations of community development.

The reef designs will be field tested for both biological and physical performance over a period of at least 5 yr. This time period was mandated by the California Coastal Commission and will begin to provide information to assess the effects of severe storm events that are likely to affect the subsidence of rocks. It will also begin to provide sufficient time for the normal developmental processes that lead to a mature biological community.

The parameters of primary interest during the reef performance monitoring are the extent to which the rock and concrete material are buried by sand, the colonization rate and survival of kelp, and the colonization of other kelp forest biota (i.e., algae, invertebrates, and fish). These data will be evaluated to determine the extent to which exposed substrates persist within each module type and the effect of substrate type (i.e., quarry rock vs concrete) and coverage in meeting the performance standards mandated for the mitigation reef.

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