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FINAL TECHNICAL REPORT
TO THE
CALIFORNIA COASTAL COMMISSION

B. Anomalous Sediments in the
San Onofre Kelp Forest

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SUMMARY

The characteristics of anomalous sediments, first observed in the San Onofre Kelp Forest (SOK) in October, 1985, are described and hypotheses regarding their origin and deposition are discussed and evaluated. The possible biological impacts of the anomalous sediments in SOK are also discussed briefly.

The anomalous sediments are remarkable for the bulk properties of high penetrability and cohesiveness. They also are finer than the sediments normally found in the San Onofre kelp forest and have a higher organic content. The anomalous sediments are generally characterized by a percentage of silts and clays of about 57 percent, a total organic carbon (TOC) of about 0.35 percent and an organic nitrogen of about 0.03 percent. The bulk, grain size and organic characteristics of the anomalous sediments are similar to those found in sediments at depths of 30 meters.

Having established that the cohesive sediments are indeed different from the normal sediments in the area, the remainder of the report erects hypotheses with and without the effects of SONGS to answer the following questions: 1) What accounts for the anomalous properties of the sediments? 2) Why did they first appear in October, 1985 about 2 years after the onset of commercial operation of SONGS Units 2 and 3? 3) Why have they only been found in the San Onofre kelp forest? 4) Why have they persisted or recurred from 1985 to the present?

Hypotheses not involving the operation of SONGS can explain the presence of fine deposits in the vicinity of SOK after about 1980. However, there is no presently documented natural mechanism which also explains the unusual bulk properties and high percent TOC and percent organic nitrogen of the anomalous sediments and the delay of their appearance in SOK until 1985. We conclude that, at present, the most parsimonious explanation for local distribution, recency, and the physical and chemical properties of the anomalous sediments involves the

operation of SONGS. The plume of SONGS Units 2 and 3 creates stagnation points in longshore current flow by itself and in conjunction with trapping by kelp in SOK. There is well-documented evidence that the cooling system from SONGS increases seston flux in the upcoast portion of SOK by about 50 percent. Finally, the cooling system ingests, kills and discharges 900 metric tons of zooplankton per year and an undetermined amount of phytoplankton that is no doubt several times higher. This organic matter is a likely source of the higher percentage of TOC and organic nitrogen in the anomalous sediments, and may serve as a source of cohesion. Conditions associated with the El Nino of 1982-1984 provide the most likely explanations for the delay of the appearance of anomalous sediments until 2 years after the onset of the full operation of SONGS. During the El Nino, the planktonic supply of organic material and clay particles was an order of magnitude lower than in 1985.

Evidence is presented indicating that the anomalous sediments have reduced the abundances of a number of kelp forest invertebrates and the coverage of turf algae in the upcoast portion of SOK.

This draft report does not address two important questions 1) How has the distribution and abundance of the anomalous sediments changed since July, 1988? ; and 2) Do the plumes of SONGS Units 2 and 3 cause the formation of significant amounts of macro-flocs that may contribute to the formation of the anomalous sediments? These questions are being addressed by on going work.

1.0 INTRODUCTION

When divers began the quarterly survey of benthic invertebrates in October, 1985, they were struck by the presence of fine, very penetrable sediments at study sites in the San Onofre Kelp Forest (SOK; see Bence and Schroeter, 1989). The sediments immediately attracted attention because they covered many of the fixed quadrats that had been sampled for years. However, the San Onofre kelp forest is a relatively sandy location, and it would not have been unusual if one or two quadrats had been mostly covered by a shift in the coarse sands that were typically found among the cobbles. A large-scale influx of the finer sands that surrounded the boulder field would have been more surprising, but only because it had not previously occurred during the study. The presence of the new sediment at the sampling stations was puzzling because it was a discrete deposit which had no obvious nearby source, it accumulated in a relatively short time (< 3 months) and its appearance was unlike local sediments. Compared to other unconsolidated materials in the boulder field, the new sediments were very fine, very easily penetrated, and could be squeezed into a ball that held its shape. Interest intensified when, instead of being transported to deeper water as expected, the sediments increased in abundance at the monitoring station in the upcoast, offshore quadrant of SOK.

Beginning in 1986, an attempt was made to estimate the abundance of the anomalous sediments throughout SOK. Between March, 1986 and July, 1988, the estimated area of rocky substrate partially or completely covered by the deposits increased and the deposits were generally most abundant along the upcoast and offshore margins of SOK.

Any substantial increase in the abundance of fine sediments in the cobble field will have adverse effects on the populations of animals and plants which live on

hard substrates (see Appendix B; Bence and Schroeter, 1989; Bence, *et al*, 1989) for a discussion of some ecological effects of the anomalous sediments in SOK). Therefore, an understanding of the distribution, abundance, origin, and mode of deposition of the anomalous sediments is important.

Before the fall of 1986, these sediments were studied as part of investigations designed to gather biological data. The sites at which substrate measurements were made was dictated by the design of the ecological sampling programs and were confined to areas predominated by cobbles and boulders. Useful estimates of the abundance of the anomalous sediments were made periodically at all the biological stations, and beginning in the fall of both 1986 and 1987, substrate characteristics were described and cores of sediment were also collected at about 65 sites in a 1200 hectare area surrounding the diffusers for SONGS Units 2 and 3. Grain size and Total Organic Carbon were measured for many of the samples, and several were subjected to mineralogical analyses. In 1989 an intensive field and laboratory study was undertaken to characterize the sediments in SOK which were thought to be anomalous and compare them to samples of normal sediments from surrounding areas, to analyze water samples from the turbid plume created by the cooling system for Units 2 and 3, and to analyze existing oceanographic and hydrological data pertinent to questions of origin and deposition.

The purpose of this report is to present the results of the various studies that have been undertaken and to provide a basis for judging the likelihood that SONGS' operation is a substantial contributing cause of the deposition of anomalous sediments in SOK. The various methods employed in these studies are discussed as the need arises, but briefly. A detailed presentation of the field and laboratory methods is contained in Appendix A. We have also included a listing of all the grain size and chemical data (Appendix C) for the benefit of the critical reader.

Section 2 of this report is a review of the evidence that there is, indeed, something that needs to be explained. We conclude that there is: the sediments in question, although variable, are distinctive and anomalous and their deposition is almost entirely restricted to the neighborhood of SOK and the period after July 1985.

Section 3 is a discussion of the potential sources and mechanisms which are the elements of any hypothesized explanations of a localized deposition of anomalous sediments during a particular time. A useful hypothesis must provide answers to several questions: What are the likely sources of the bulk material? How was it transported to the site? Why was it deposited in a restricted area? How did it persist or recur in the face of wave-erosion?

Section 4 of the report is a discussion of background data which are pertinent to all hypotheses concerning the origin and deposition of sediments in SOK. Whereas the previous section is a listing of possible mechanisms and their combinations, this section is a physical discussion of the mechanisms and a review of the evidence that bears on their relative likelihood.

Section 5 is an evaluation of several alternative hypotheses erected to explain the appearance and persistence of anomalous sediment deposits in SOK. Both the origin of the deposits and the mechanism of deposition are considered.

2.0 DESCRIPTION OF ANOMALOUS DEPOSITS AND OTHER SEDIMENTS NEAR SONGS

2.1 Character of the Sediments

The anomalous characteristics of the sediments which were first seen in 1985 at the benthic monitoring stations were their fineness and unusual bulk characteristics. They were very soft and penetrable and were cohesive. Throughout this report when we use the term "cohesive," we use it in the everyday sense of "sticking together tightly." When a handful of the anomalous sediments was squeezed into a ball it held its shape, and when one pressed the sediments the resultant handprint remained for many minutes. The consistency of the sediments was also unusual for the area. It was much like that of pudding. The surface had a somewhat gelatinous "crust" which, when struck, vibrated 30 or 40 cm away. Although the deposit was more than 50 cm deep in places, divers could easily thrust their arms through it and feel the cobbles and boulders beneath. Such penetrability is unusual and suggests high water content.

The cohesive sediments at the benthic monitoring station in upcoast SOK (SOKU45=F1 in Figure 6) compacted with time. After about 10 months they were much firmer, but it was still possible to work one's fingers into the sediment or force a ruler through it. From 1986 to 1989 there was little additional change in the characteristics of that deposit. However, with time the surface took on a coarser look and often bore ripples, and the deposit appeared less homogeneous. In 1989, the bottom 10 centimeters or so of material was darker, seemed finer, and appeared to have higher water content than the overlying sediments. Although this deposit of anomalous sediments has been present since fall, 1985, the shape has varied and the constituent grains of sand and silt making up the deposit may well have been

replaced several times over. We have no data on the turn-over rate of the sediments, but it is clear that the deposits we have observed were not static bodies.

The anomalous sediments at the downcoast monitoring station were present until July, 1988. Since 1985 we have also observed anomalous sediments at many other stations in the San Onofre Kelp Forest. Some formed thick, discrete patches as at SOKU45 (=F1), others occurred as a thin (2-3 cm) deposit overlying moderately coarse sands or covering the surface of boulders and cobbles.

We collected samples of the new sediments at the upcoast benthic station (SOKU45 (=F1)) when it first appeared. In May 1986 we resampled that deposit and also collected cores at three other stations in the kelp forest and at a station directly offshore in 30 m of water (Figure 1). In fall, 1986 we visited 67 sites in a 1200 hectare area that included the San Onofre Kelp Forest (Figure 2). The intent of the survey was to document the distribution of anomalous sediments and to compare the grain size distribution and total organic carbon content of anomalous and other sediments. In 1987 a second, similar survey was conducted and most of the sites visited in 1986 were again sampled (Figure 2).

A fourth major collection of sediments was made in early 1989. Samples were taken at stations at three water depths (10m, 20m, & 30 m) near the San Mateo, San Onofre and Barn Kelp Forests and at a few stations at kelp bed depths (Figure 3). During the 1989 survey, cores of sediment were brought to the surface, kept awash in water and tested with a penetrometer and vane-shear in the field before being sent to laboratories for assessments of grain size distribution, TOC, and N. A penetrometer measures the force required to drive a probe of a given diameter a fixed distance into the sediment. A vane-shear measures the torque required to cause failure, or slippage within a sediment sample. The vanes are forced into the sediment and torque applied until the vanes rotate (Appendix A). Samples from eight stations were also tested with a "shaker" analysis which estimates

the resistance of a sediment to suspension. A perforated disk is moved up and down over sediment in a large core for a fixed time and seston concentration is measured (Appendix A).

When first observed, the anomalous sediments were qualitatively different from the coarser sands at our study sites and readily distinguished. However, during the fall, 1986 survey it became apparent that the new sediments, when compacted, were at one end of a continuum of grain size, cohesiveness, and penetrability. We erected the following tests for anomalous sediments:

1. Is the consistency pudding-like?
2. When pressed, will it hold a hand print?
3. When squeezed, does it hold its shape?
4. When shaken into the water, does it form a cloud of turbidity rather than sink?
5. Is it talc-like or sticky?

The answer to each of these questions was "yes" for the anomalous sediments collected earlier at the benthic monitoring station and for the sediments at the 30-m station further offshore. In practice, tests 4 and 5 were widely ignored because they were difficult to apply in a consistent manner and many of the divers didn't think they were good discriminants. In this and all later surveys, unconsolidated materials were considered to possess anomalous properties (were called "ooze" in field notes) if the answer to question one or question two or question three was "yes." During the 1986 and 1987 surveys the divers applied the tests and recorded their judgement. During the 1989 survey the tests for anomalous characteristics were expressed in a slightly different fashion and formalized in a data sheet (Appendix A: Figure A1). Divers recorded the results of the tests and the assessment of sediment type was made later based on the test results and field notes.

There were, of course, occasions when the tests of penetrability and cohesiveness were not definitive and the answer to each question was closer to an uncertain "maybe" than a definite "yes." When the field notes indicated uncertainty or two observers disagreed in their assessment, the sample was classified as "intermediate." There was no protocol or other attempt at standardization for describing other sediments. However, all the investigators involved in these surveys had years of experience diving in southern California's coastal waters and tended to use similar suites of descriptors. Where field notes indicated that sand was overlain by anomalous sediments the sample was termed "mixed".

The results of all three surveys were similar (Table 1). On average, the rankings of sands and silts into categories of increasing grain size by divers in the field corresponded reasonably well with rankings based on the percentage of silts and clays ($\phi > 4$). Since there was no attempt at standardization in categorizing sands and silts, different observers used somewhat different descriptions and when all the data were combined it was apparent that several of the categories were not different (Table 2). Although it is reassuring that observers can distinguish coarse from fine sands in the field, the important result is that they can distinguish sediments with anomalous characteristics from all others. Sediments which were judged anomalous in the field were significantly different from other unconsolidated materials in percent of silts and clays, percent of clay ($\phi > 8$), total organic carbon, and total organic nitrogen (Tables 2 & 3). Furthermore, although the percent TOC in the sediments was directly related to the percent of silts and clays present, total organic carbon was still significantly higher in anomalous sediments when the percent of materials finer than $\phi 4$ was held constant in the analysis (Table 3). The percentage of silts and the percentage of clays also tend to vary together, but when the percentage of silts is used as a covariate in the analysis, the anomalous sediments still have a higher clay content than the other sediments (Table 3). The

1989 measurements with penetrometer and vane-shear corroborate the divers' *in situ* assessments. Samples which were judged to be anomalous proved to be more penetrable and more easily sheared than the other sands and silts (Table 4).

What all this means is that investigators are able to distinguish very fine grained sediments from coarser sands in the field, and they are able to distinguish fine sands and coarse silts that are highly penetrable and cohesive *in situ* from fine sediments that do not possess those characteristics. The former sediments were called "ooze" in the field notes. Although the term may be objectionable on several counts, it is worth retaining as a convenient shorthand for the moment. The results of the various analyses allow us to define "ooze" as unconsolidated sediments which are very penetrable and cohesive *in situ*, are composed, on average, of about 57 percent silts and clays, 3.0 percent clays and 0.35 percent total organic carbon (Table 2). The point we wish to make here is that the compacted "ooze" found in the kelp forest and the sediments located 200 m to 600 m farther offshore at 20 and 30 m depths are indistinguishable by divers in the field and were all designated "ooze". Laboratory analysis of grain size and organic carbon also show that these sediments are significantly different from "Other Sediments". In a search for more acceptable term we have adopted the relatively neutral "anomalous" to describe the characteristics of "ooze". However, the characteristics of the sediments described as "ooze" are anomalous only in relation to the coarse sands normally found in the kelp forest and the sands and coarse silts upcoast and downcoast at the same and shallower depths. There is no reason to believe that the characteristics are anomalous relative to the normal sediments found in deeper water.

The mineralogy of the anomalous sediments in the San Onofre Kelp Forest appears unremarkable. A preliminary investigation of the mineralogy of the anomalous sediments by Pierce (1986) indicated that the sands and silts were composed of quartz, feldspar, mica, and other aluminosilicate minerals. Shell

fragments, diatoms, and foraminifera were also present. These mineral species are normal constituents of sediments for this section of coast (Gayman, 1986). X-ray diffraction analysis indicated that the anomalous sediments did not stand out from the other sediments in the area with regard to the mix of clay minerals (Table 5).

What do the various characteristics which are statistically associated with "ooze" tell us about these materials? These distinctive sediments have been called "cohesive" because a handful will stick together in a ball. The property of cohesion by itself, though, is not fully separable from effects of high water content on both the field identifications and strength measurements, which is one of the reasons we have generally adopted the more neutral name "anomalous sediment." Non-cohesive grains will initially settle from suspension in a more or less loose packing, with excess water between grains. Then they will gradually shake down into closer packing, expelling the excess water upward through the channels between grains. These channels are narrower for finer grains, so the rate of compaction falls off steeply with grain size. Rapidly deposited and thick accumulations of the finest silts can retain excess water for many days. For example, after slumping, the firm sands and silts (median phi 5-6) near the head of Scripps Canyon were sufficiently liquified that a diver could force his arm nearly a meter into the bottom (Marshall, 1978). Within about a month the sediment was noticeably more compact, but it took about six months to return to its original state.

If a sediment is cohesive because it contains some soft sticky grains or because the grains have a sticky coating, it is all the more likely to retain excess water longer, for several reasons. The cohesion retards relative motions of grains toward closer packing, and the cohesive component may obstruct the channels between grains. If cohesion has aggregated grains into irregular flocs before they settled, the initial packing may be very loose, giving a high initial water content.

The properties of cohesion and high water content are likely to be associated, then, but they have opposite effects on shear strength. With or without cohesion between grains, sediments will show some shear strength due to interlocking or friction between grains. This kind of shear strength is very sensitive to loading: it increases greatly if the grains are forced together by an applied pressure. On the other hand, it will decrease greatly if the grains are kept apart by excess water, as in the extreme case of a quicksand.

With these things in mind, we can consider the meaning of the various tests applied to anomalous and normal sediments. The anomalous properties of retaining a ball-shape or a handprint against gravity definitely show that the anomalous sediments have perceptible shear strength under the lightest loading, while normal sediments do not. These are the tests that let us describe the anomalous sediments as cohesive.

The tests of penetrability and vane-shear strength measure shear strength under various conditions of considerable loading due to the test itself. The stress under a penetrometer foot, for instance, varies from uniaxial compression at the middle to pure shear at the edge, equivalent to a varying mix of shear and pressure. Under these tests with loading, the anomalous sediments generally show lower shear strength than normal sediments. This can be ascribed to high water content: the reduction of frictional shear strength more than offsets the strength due to cohesion. These measures of loaded shear strength may best be taken as measures of excess water. The quaking test (or earlier designation as "pudding-like") is probably also a measure of water content: frictional losses in a well-compacted sediment will prevent the visible propagation of waves, but excess water will reduce these losses so that a wave can travel a few feet before it damps out. In short, the ball and print tests indicate unloaded shear strength due to cohesion between grains. The

penetrometer, vane-shear, and quaking tests indicate excess water content, probably, but not necessarily, associated with cohesion.

The results of shaker measurements on eight samples from San Onofre are shown in Figure 4. All the samples showed about the same suspension threshold, at a frequency somewhere between 5 and 8 cycles/sec, and about the same increase of suspension with frequency above threshold. The differences among samples at the frequencies of 5 and 6 cycles/sec were 20% of the mean or less, and were not systematically related to grain size or anomalous character in the samples.

Shaker results on a variety of sediments have shown a reproducible relation to suspension measurements in a unidirectional flume, but they have not yet been correlated with observations of net suspension or erosion by ocean waves of period 6 to 20 seconds. The conditions of loading, and probably also the seston profiles near the bottom, are very different for the three cases of the shaker, the one-directional flume, and the sea-bottom under wave, and the correspondence between shaker and flume may not extend to net suspension by waves. These caveats aside, the shaker results suggest that if there are real differences in resistance to wave erosion by waves among the San Onofre samples, they are probably not large.

In summary, the distinctive sediments that have appeared on hard substrates in the San Onofre kelp forest are not unusual in mineral composition and are what one would expect based on a knowledge of terrestrial sources. Their anomalous characteristics are that they are cohesive *in situ*, appear to have a high water content, have a higher proportion of silts and clays than is usually found in shallow water, have a higher content of both total organic carbon and total organic nitrogen than normally found in local sands, are rapidly deposited in relatively large quantities, were not seen prior to 1985, and have persisted or increased over a period of several years.

2.2 Spatial and Temporal Distributions

2.2.1 Observations at Sites with Fixed Quadrats

Two stations in the San Onofre Kelp Forest, one in the San Mateo Kelp Forest and one in the Barn Kelp Forest have 40 fixed quadrats marked with steel stakes (Figure 6 and Bence, et al, 1989). The anomalous sediments were first observed at the stations in SOK and were still present at the upcoast station in 1989. These stations are of particular interest because the history of the deposits there are so well-known.

The patch of anomalous sediments at the array of fixed quadrats at SOKU45 (=F1) was first observed in October, 1985. The anomalous sediments were not observed on the previous visit which was in July 1985. This station was visited four to six times a year for surveys or maintenance. Visibility was generally 2 m to 5 m, but was occasionally greater than 20 m. As a result, we can state categorically that the anomalous sediments were not present at any of the stations prior to 1985.

The deposit at SOKU45 (=F1) increased in size over the next 14 months. In December, 1986, anomalous deposits were present in nearly 90 percent of the quadrats (Figure 5). In April 1989 the deposit covered about 1300 m² and two similar deposits of roughly the same size and character were found nearby. This temporal pattern indicates accretion of a relatively stable deposit.

At SOKD45 (=F2) the new deposits were first observed in March, 1986. Abundance was highest in September, 1986, and declined by December, 1986, when the deposits were present in only 3 percent of the quadrats (Figure 5). In January 1989, two patches of the anomalous sediments were observed at SOKD45 (=F2). The sediments were very fine and very easily penetrated. They overlaid patches of coarser sand in the cobble bed and covered about 40 m². They disappeared during a

period of large swells in February, 1989. Anomalous deposits were never observed in fixed quadrats at SMK45 (=F3, Figure 5) or BK

2.2.2 Observations in Random Quadrats in SOK and SMK

Other biological monitoring programs made use of a large number of stations arrayed in uniform grids overlying the San Onofre and San Mateo Kelp Forests. At each of these fixed stations, 3 to 5 random quadrats were examined on each survey (Figure 6 and Bence, et al, 1989).

Systematic searches for the anomalous deposits throughout SOK and SMK were begun in March, 1986. At this time, such deposits were observed at three stations very close to the array of fixed quadrats at station SOKU45 (=F1; Table 6; station locations are in Figure 6). The frequency of occurrence and depth of the deposits increased in SOK through July, 1988 (Table 6; Figures 7 - 9). The increase was greatest in the upcoast, offshore portion of SOK, where the anomalous deposits occurred at 7 out of 10 stations. In general, the deposits tended to be most abundant along the upcoast and offshore margins of the kelp forest in SOK (Figures 7 - 9). The frequency of occurrence generally increased in the offshore portion of SOK, whereas it was generally lower, not as deep, and fluctuated more in SOKN and the inshore quadrants of SOK.

Deposits of fine sands were found at one station on the downcoast, offshore margin of SMK and were identified in the field as anomalous on two occasions. They differed from those in SOK by having lower percentages of TOC and of silts and clays.

2.2.3 Sediment Samples from the SONGS Area

Analysis of sediment samples taken in October, 1986 indicated relatively high percentages of silts and clays along the upcoast margin and about 200 meters offshore of the offshore margin of the San Onofre Kelp Bed (Figure 10). The percent of silts and clays at these sites was similar to that found at depths of 30 meters (mean = 64.8).

Many more samples were available from the margin of the kelp bed in July, 1987. As in the October, 1986 sample, percentages of silt plus clay were high along the upcoast margin of the bed and 200 meters offshore (Figure 10). Sediments with high silts and clays were also found along the inshore and downcoast margins and upcoast and offshore of the Unit 2 diffuser.

In summary, anomalous deposits with high percentages of silts and clays were first observed near the upcoast, offshore margin of SOK in October, 1985. Their distribution and abundance increased during the following 14 months, primarily along the offshore and upcoast margins of SOK. Deposits with similar high values of silts and clays have been seen near SOKU45 (=F1) in the past. These deposits differ from the anomalous sediments in two ways. First, the percentage of TOC was 1/3 to 1/2 of that in the anomalous sediments (Table 9). Second, they were much less persistent. Whereas the anomalous sediments have persisted for at least four years after they were first sited, the fine sediments observed before 1985 lasted no longer than three months (Figure 11). Fine sediments were observed along the offshore downcoast margin of SMK. They differed from the anomalous sediments in SOK by having a lower percentage of silts and clays and lower TOC.

The last large-scale, systematic survey of anomalous sediments was conducted in July 1988. We do not know how the distribution and abundance of such sediments has changed since then, but a 1989 survey is scheduled.