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POTENTIAL IMPACT OF DEEP SEABED MINING ON THE LARVAE OF TUNAS AND BILLFISHES

Walter M. Matsumoto

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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ABSTRACT

Assessment of the probable impact of deep seabed mining on the eggs and larvae of tunas and billfishes is made, based largely on studies of the effects of sedimentation on eggs, larvae, and adults of freshwater, estuarine, and a few marine fishes. Most of the changes to the environment resulting from mining, such as increased suspended sediment particles, reduced illumination due to turbidity, mixing of cold bottom water with surface water, and changes in trace metals, salinity, and oxygen levels of the surface water, are not extensive enough to endanger tuna and billfish eggs and larvae. One probable effect, temperature of discharge, is acknowledged, but its effects are expected to be insignificant. Cold bottom water (4°-10°C) discharged over the side of the mining ship and falling directly onto tuna eggs and larvae at the surface could cause thermal shock, resulting in the termination of embryonic development, development of abnormal larvae, and loss of equilibrium by the larvae. Losses from thermal shock, estimated annually at 15.3 metric tons (MT) of skipjack tuna and 10.7 MT of yellowfin tuna, representing 0.16 and 0.04% of the total annual catches of the respective species in the eastern Pacific northern fishery (the fishery north of Mexico), are insignificant and are not likely to have any noticeable impact on the fishery. These losses could possibly be increased fourfold, if the mining ship were to act as fish aggregating devices, but even at these higher levels, the impact on the fishery would be negligible.

INTRODUCTION

In the Programmatic Environmental Impact Statement prepared by the National Oceanic and Atmospheric Administration (NOAA 1981) pursuant to the Deep Seabed Hard Mineral Resources Act and the National Environmental Policy Act, several unresolved impacts from seabed mining of manganese nodules in the eastern Pacific Ocean (lat. 5°-20°N, long. 110°W-180°) are identified as having the potential to cause adverse effect on the biota. One potential unresolved impact is the effect of particulates discharged at the surface on fish larvae.

Recent studies on the alteration of the environment and the effects on phytoplankton, macrozooplankton, and certain fish species resulting from mining operations in the area have been completed (Ozturgut et al. 1980; Chan and Anderson 1981; Hirota 1981; Lavelle and Ozturgut 1981; Lavelle et al. 1982). These studies include data on the discharge characteristics, surface plume, and effects of suspended particulate matter on phytoplankton and macrozooplankton of the area. Laboratory experiments with two species of tunas exposed to seawater containing suspended particulate matter in concentrations similar to that expected from mining operations have been done also (Barry 1978). Based on these experiments, it was determined that adult tunas would not be affected significantly by discharges from mining operations. The possible effects of particulates on the survival and growth of the larvae, however, have not been addressed adequately.

This report describes the biology of tunas and billfishes in the Pacific Ocean, with emphasis on the prime mining areas, examines the probable effects of mining on eggs, larvae and adults, and discusses the significance of adverse effects on the fisheries.

DISTRIBUTION AND BIOLOGY OF TUNAS AND BILLFISHES IN THE PACIFIC OCEAN

Distribution

Adults

The distribution of the tunas in the Pacific Ocean has been described at length by Blackburn (1976) and Sund et al. (1981). Of those species of tunas and billfishes which occur more or less continuously across the ocean, the following, due to their commercial importance, are of concern in the area of prime interest for commercial deep seabed mining: yellowfin tuna, *Thunnus albacares*; bigeye tuna, *T. obesus*; skipjack tuna, *Katsuwonus pelamis*; blue marlin, *Makaira nigricans*; and striped marlin, *Tetrapturus audax*.

The areal distribution of the tunas does not vary much by species (Figs. 1-3), but there are differences in abundance within the distributional range. Yellowfin tuna are distributed between lat. 45°N and 45°S in the western Pacific west of the 180th meridian, between lat. 40°N and 40°S in the central Pacific west of long. 140°W, and from Central America to lat. 35°S in the eastern Pacific. The distribution is narrowed to lat. 20°N and 30°S in the eastern central Pacific at long. 115°-120°W. Areas of abundance generally are restricted to within 20° of the Equator. Bigeye tuna, a more temperate species, is found in cooler waters than the yellowfin tuna. It is distributed from lat. 45°N to nearly 50°S in the

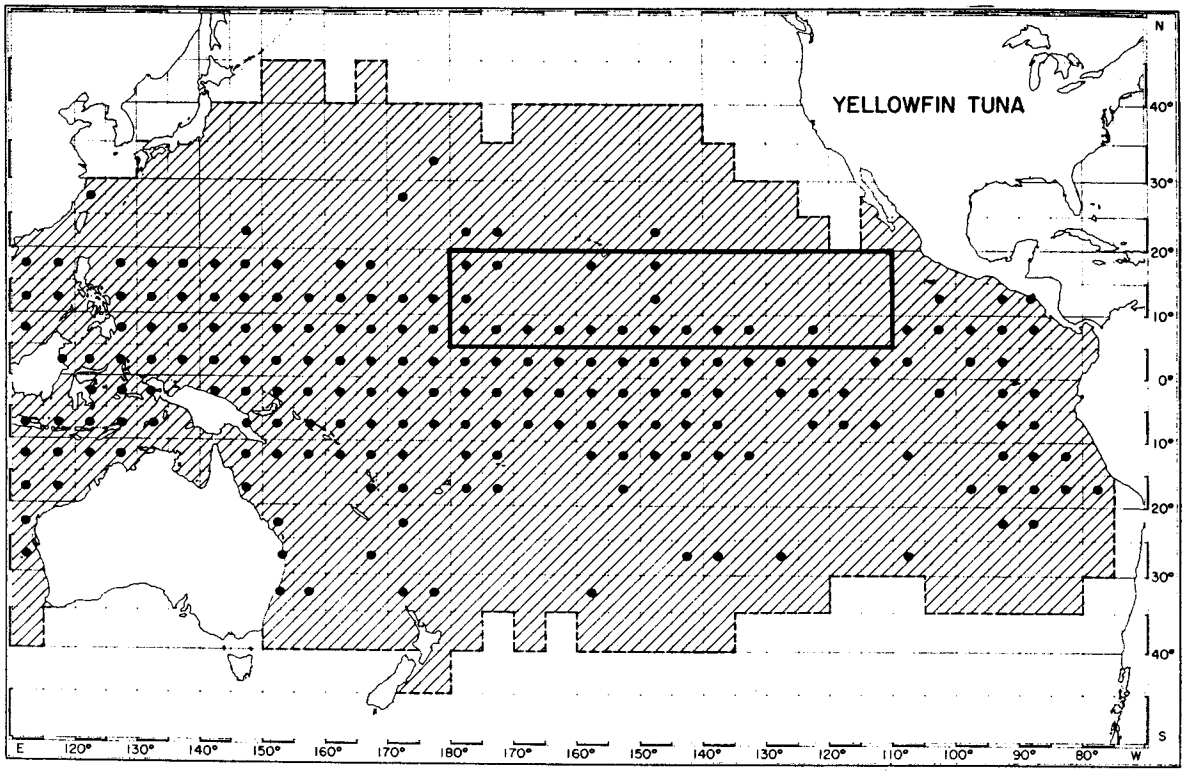

Figure 1.--Distribution and areas of abundance of yellowfin tuna in the Pacific Ocean. Hatched area represents range of distribution; dots represent catches of more than 1 fish per 100 hooks ([Japan.] Fisheries Agency, Research Division 1970, 1972, 1973, 1981; Shingu et al. 1974; Calkins 1975; [Korea.] Fisheries Research and Development Agency 1981).

western Pacific, from lat. 40°N to 45°S in the central Pacific, and lat. 35°N to 40°S in the eastern Pacific east of long. 130°W. Unlike that of yellowfin tuna, the distribution of bigeye tuna is not constricted in the eastern central Pacific. The areas of abundance are skewed further to the north in the central and eastern central Pacific (between long. 165°E and 125°W) and to the south in the eastern central and eastern Pacific (east of long. 140°W). Skipjack tuna are distributed between lat. 45°N and 45°S west of the 180th meridian. The distribution narrows gradually to the east and is constricted off Baja California and offshore from the South American Continent. The areas of abundance are indicated by the extent of present fisheries. In the western Pacific, west of the 180th meridian, the area of abundance extends from lat. 45°N to about 20°S and narrows rapidly to the area slightly east of the Hawaiian Islands. In the eastern Pacific, the area of abundance extends from Baja California to central Chile along the coast and narrows seaward to about long. 140°W. The apparent gap in the area of abundance between long. 140° and 160°W is due to the absence of fishing effort.

The distribution of billfishes does not differ greatly from that of the tunas. Blue marlin occurs between lat. 45°N and 40°S in the western Pacific, lat. 40°N and 35°S in the central Pacific, and lat. 35°N and 35°S in the eastern Pacific (Fig. 4). The area of abundance lies between the Equator and lat. 25°N in the western half of the ocean and between lat. 5°N and 20°S in the eastern half. The distribution of striped marlin is nearly

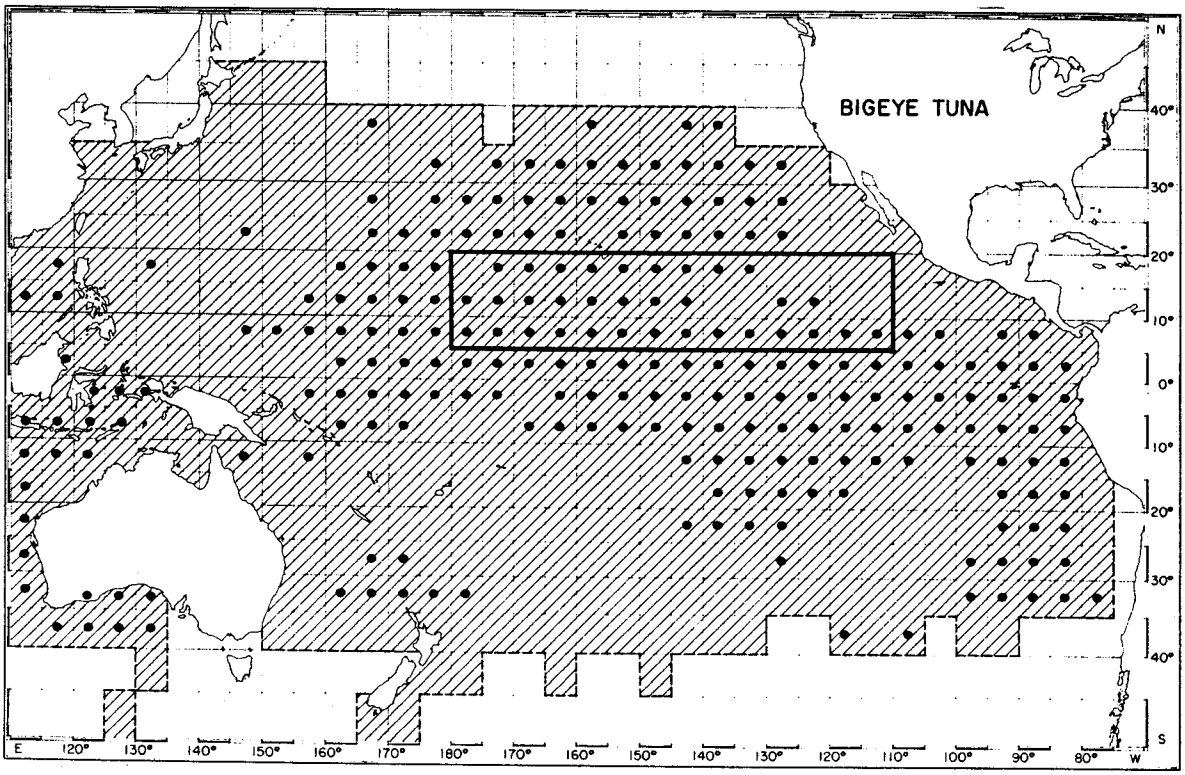

Figure 2.--Distribution and areas of abundance of bigeye tuna in the Pacific Ocean. Hatched area represents range of distribution; dots represent catches of more than 0.8 fish per 100 hooks ([Japan.] Fisheries Agency, Research Division 1970, 1972, 1973, 1981; Shingu et al. 1974; [Korea.] Fisheries Research and Development Agency 1981).

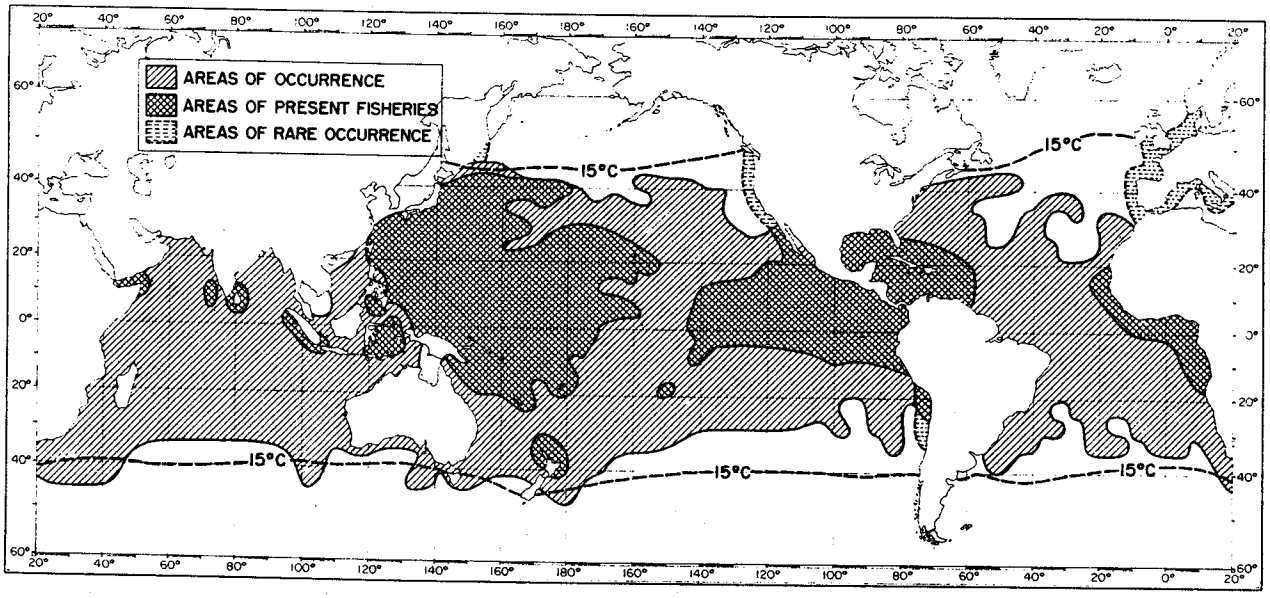

Figure 3.--Skipjack tuna distribution (hatched areas) and fisheries (cross-hatch areas) in the major oceans. The mean 15°C isotherms represent maximum late summer poleward displacement (Matsumoto et al. 1984).

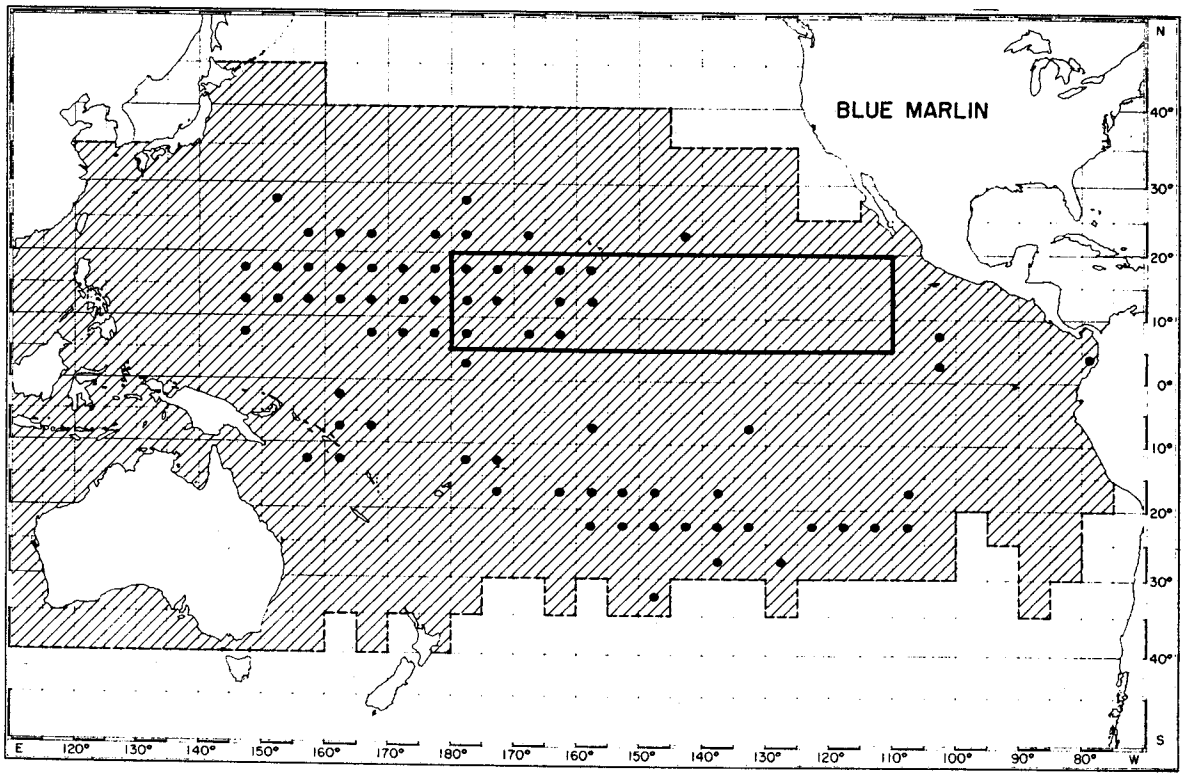

Figure 4.--Distribution and areas of abundance of blue marlin in the Pacific Ocean. Hatched area represents range of distribution; dots represent catches of more than 0.3 fish per 100 hooks ([Japan.] Fisheries Agency, Research Division 1970, 1972, 1973, 1981; Shingu et al. 1974).

similar to that of blue marlin in the central and eastern Pacific. In the western side, however, the poleward limits are at lat. 50°N and 50°S (Fig. 5). The area of abundance lies in a northwestward direction from the northwestern coast of South America to Japan, and is situated to the north of the center of blue marlin abundance. The southern edge of striped marlin abundance overlaps the northern edge of blue marlin abundance in the eastern Pacific.

The distribution of tunas and billfishes is influenced by surface currents and temperature. In the Pacific Ocean, warm currents (North and South Equatorial Currents) flow westward across the ocean (Fig. 6). At the western end, the currents are deflected poleward and carry warm water to higher latitudes. Cool currents flow eastward across the ocean at about lat. 45°N and 45°S. At the eastern end, the main body of both currents turn toward the Equator and carry cold water to lower latitudes. The current flow affects the climatic surface temperatures so that the western side of the ocean is characterized by a very broad belt of tropical water, a very narrow belt of temperate water, and a rapid transition to the cold waters of higher latitudes. The eastern side is characterized by a very broad belt of temperate water and a very narrow belt of tropical water (Brock 1959). This results in the wider distribution of tunas and billfishes in the western side and the narrower distribution in the eastern side.

Temperature ranges in the entire distributional area and in areas where abundance is high enough for commercial fishing have been published

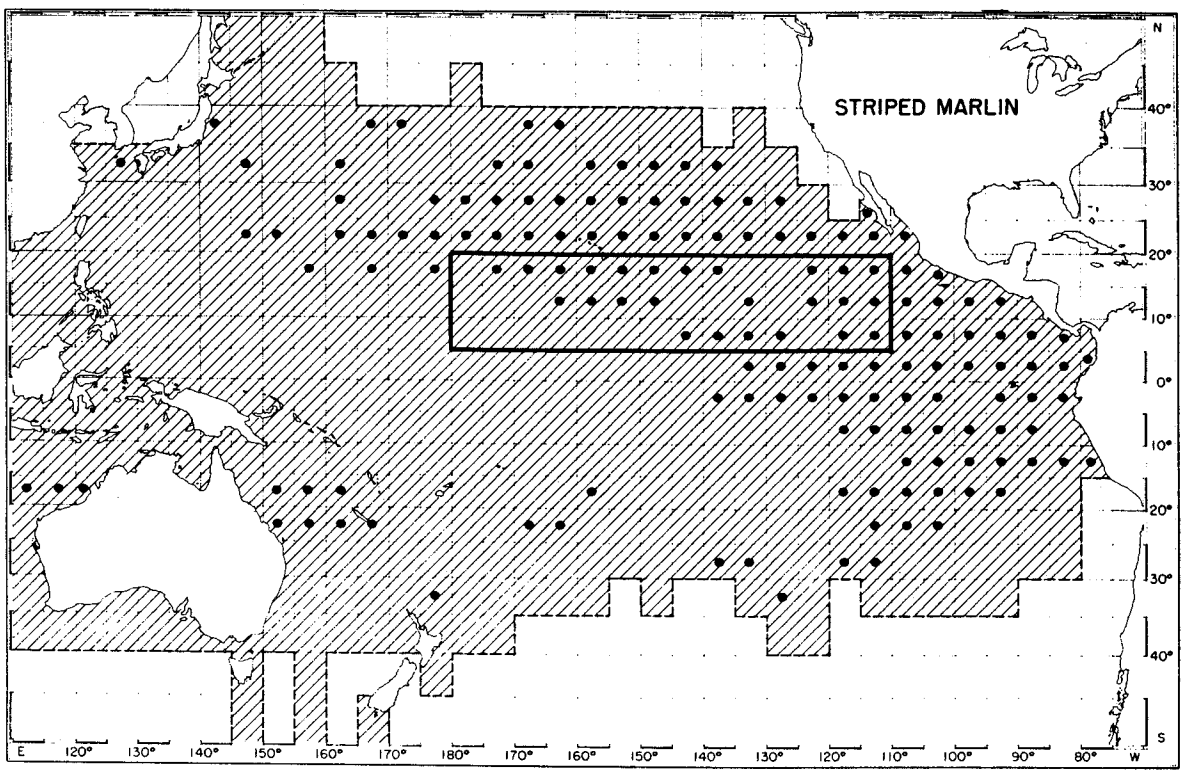

Figure 5.--Distribution and areas of abundance of striped marlin in the Pacific Ocean. Hatched area represents range of distribution; dots represent catches of more than 0.4 fish per 100 hooks ([Japan.] Fisheries Agency, Research Division 1970, 1972, 1973, 1981; Shingu et al. 1974).

for the tunas on a worldwide basis (Laevastu and Rosa 1963). These are, respectively, 11°-28° and 18°-22°C for bigeye tuna, 18°-31° and 20°-28°C for yellowfin tuna, and 17°-28° and 19°-23°C for skipjack tuna. Other reports (Robins 1952; Uda 1957; Jones and Silas 1963; Broadhead and Barrett 1964; Williams 1970; Sharp 1978) indicate an even wider temperature range for skipjack tuna: 14°-30° and 17°-30°C. At the northern and southern extremes of their distribution, the tunas almost certainly respond directly to temperature changes (Uda 1957; Schaefer 1961). The direct influence of surface temperature on distribution is less obvious in the tropics where temperature is relatively uniform throughout the year (Laevastu and Rosa 1963). Here the distribution and abundance of tunas are controlled mainly by the distribution and abundance of suitable food, such as in areas of upwelling and convergence (Blackburn 1965), by vertical thermal structure (Green 1967; Sharp 1978), and by oxygen levels (Hanamoto 1975; Sharp 1978). In the eastern Pacific yellowfin tuna fishery, Green showed that purse seining was more successful where the top of the thermocline did not exceed 18 m and where the mean temperature gradient was sharp (>0.55°C/m) within the thermocline. Sharp (1978) noted that the optimum fishing for this species appeared to occur where the 23°C isotherm was shoaler than 50 m and the 15°C isotherm was above 80 m.

Tunas and billfishes are distributed vertically to great depths. The vertical distribution of tunas and some billfishes has been estimated by various methods. Although bigeye and yellowfin tunas were distributed to a depth of 380 m, based on experimental vertical longline catches (Saito

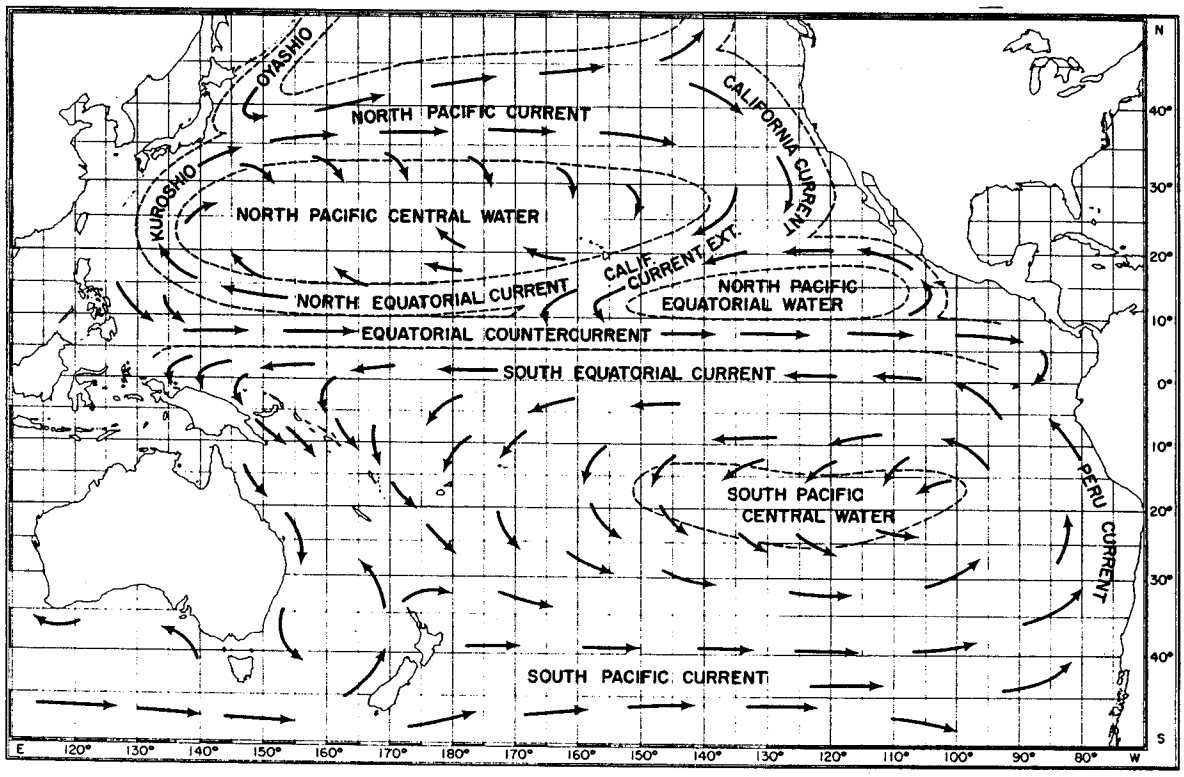

Figure 6.--Ocean current systems in the Pacific Ocean.

1973; Saito and Sasaki 1974), the depths of greatest concentrations were stratified with some overlap among species. Striped marlin were taken mostly at 150-290 m, yellowfin tuna at 150-300 m, and bigeye tuna at 290-380 m. Skipjack tuna, which have been considered surface dwellers, mainly because they are largely taken by surface fishing gear, were observed at depths of 152 m from submarines (Strasburg et al. 1968). They have been detected at 235 m with echo sounders (Yamanaka et al. 1966), and at 263 m with ultrasonic devices (Dizon et al. 1978).

Larvae

The distributional range of tuna larvae is less extensive than that of the adults. Yellowfin tuna larvae (Fig. 7) range from lat. 35°N to 25°S in the western Pacific and from lat. 30°N to 25°S in the central Pacific. The range narrows to about lat. 10°N and 20°-25°S in the east central Pacific (long. 130° to 140°W) and to lat. 26°N and 10°S in the eastern Pacific. The north-south distribution of bigeye tuna larvae (Fig. 8) is less extensive than that of yellowfin tuna larvae. It ranges from lat. 35°N to 25°S in the western Pacific, from lat. 25°N to 10° or 15°S in the central Pacific and lat. 20°N to 10°S in the eastern Pacific. The distribution constricts to about 10° north and south of the Equator at about long. 135°-155°W and lat. 15°N to the Equator at about long. 125°W. Skipjack tuna larvae are distributed over the widest north-south range among tuna species in the western half of the ocean (Fig. 9). The range extends from lat. 35°N to 40°S in the western sector, and lat. 30°N to 35°S in the central sector, but constricts sharply to lat. 10°-15°N and 20°S east of long. 145°W and lat. 15°N east of long. 100°W. In all species the poleward limits coincide quite well with the 25°C surface isotherm.

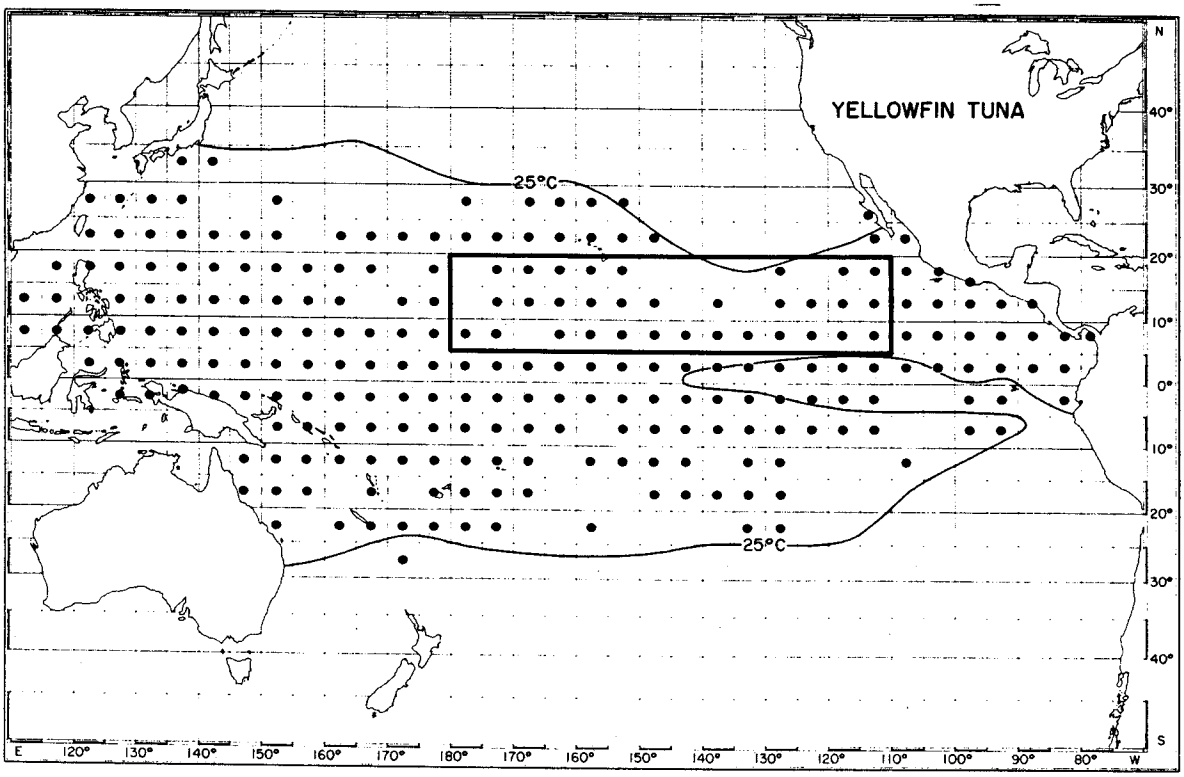

Figure 7.--Distribution of yellowfin tuna larvae in the Pacific Ocean (Klawe 1963; Matsumoto 1966; Ueyanagi 1967, 1969; Hirota 1977; Nishikawa et al. 1978).

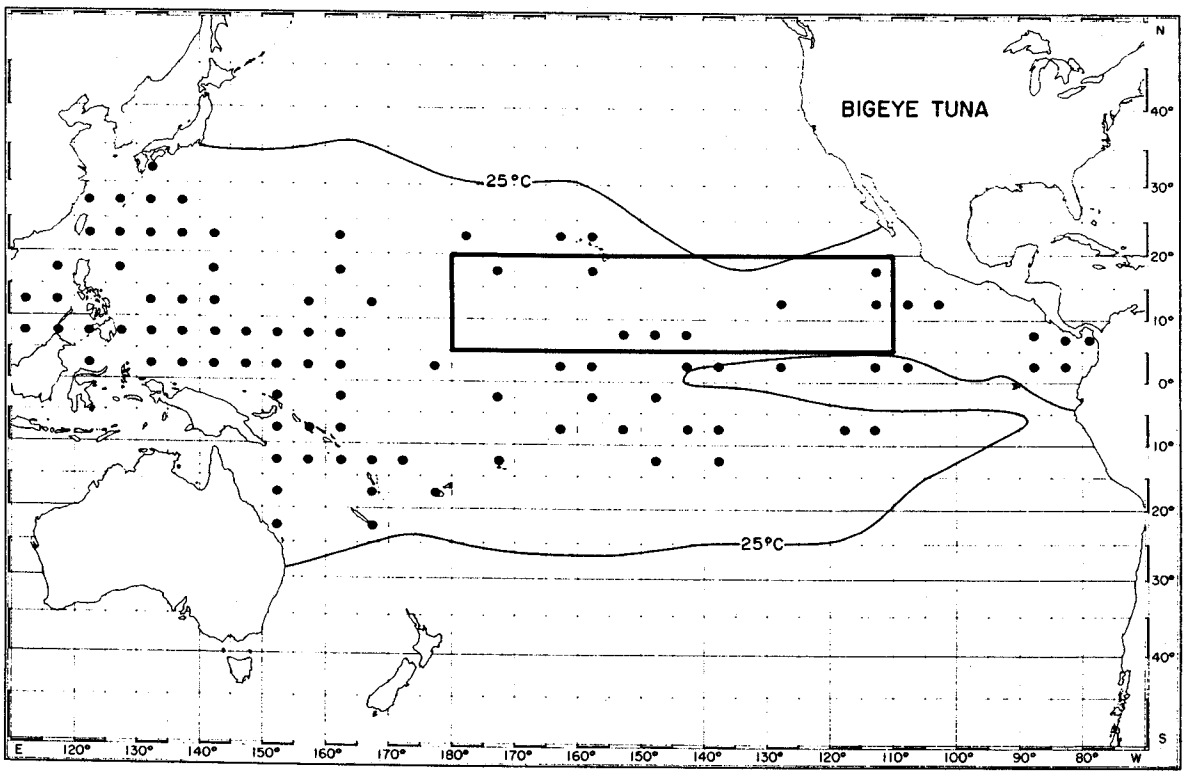

Figure 8.--Distribution of bigeye tuna larvae in the Pacific Ocean (Matsumoto 1966; Ueyanagi 1969; Nishikawa et al. 1978).

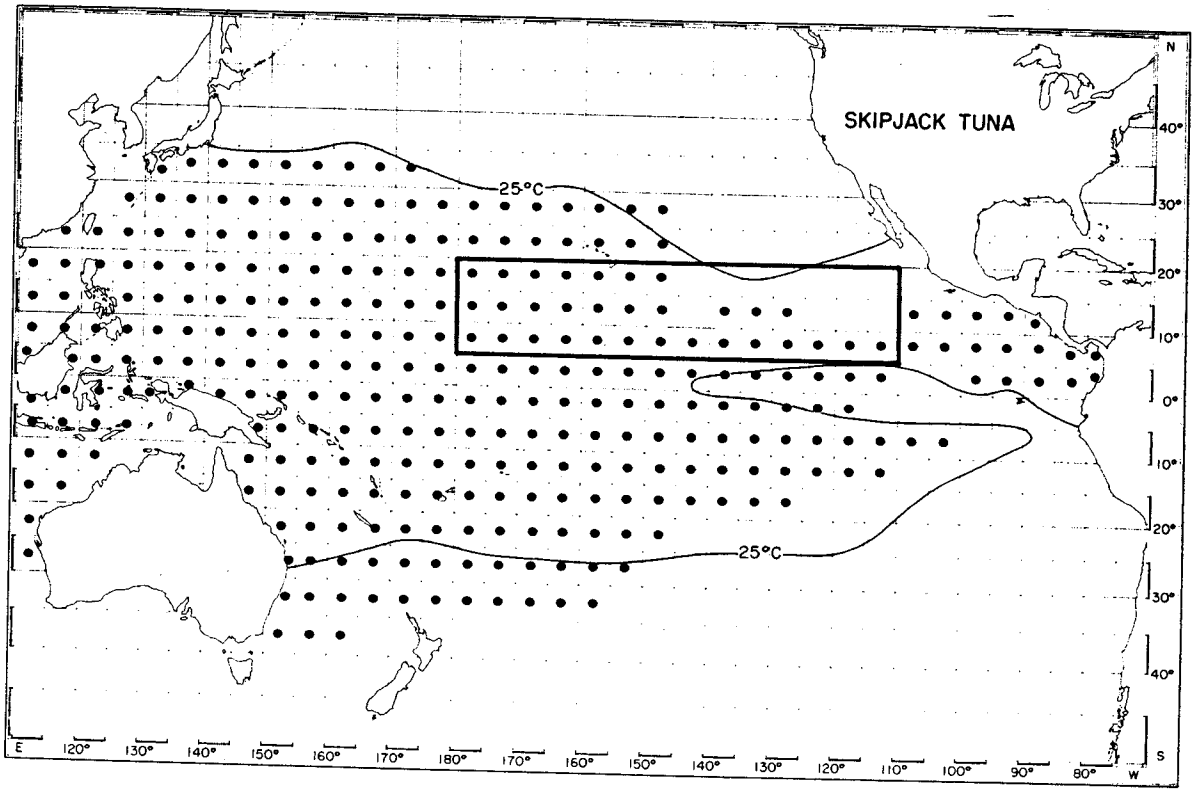

Figure 9.--Distribution of skipjack tuna larvae in the Pacific Ocean (Hirota 1977; Matsumoto et al. 1984).

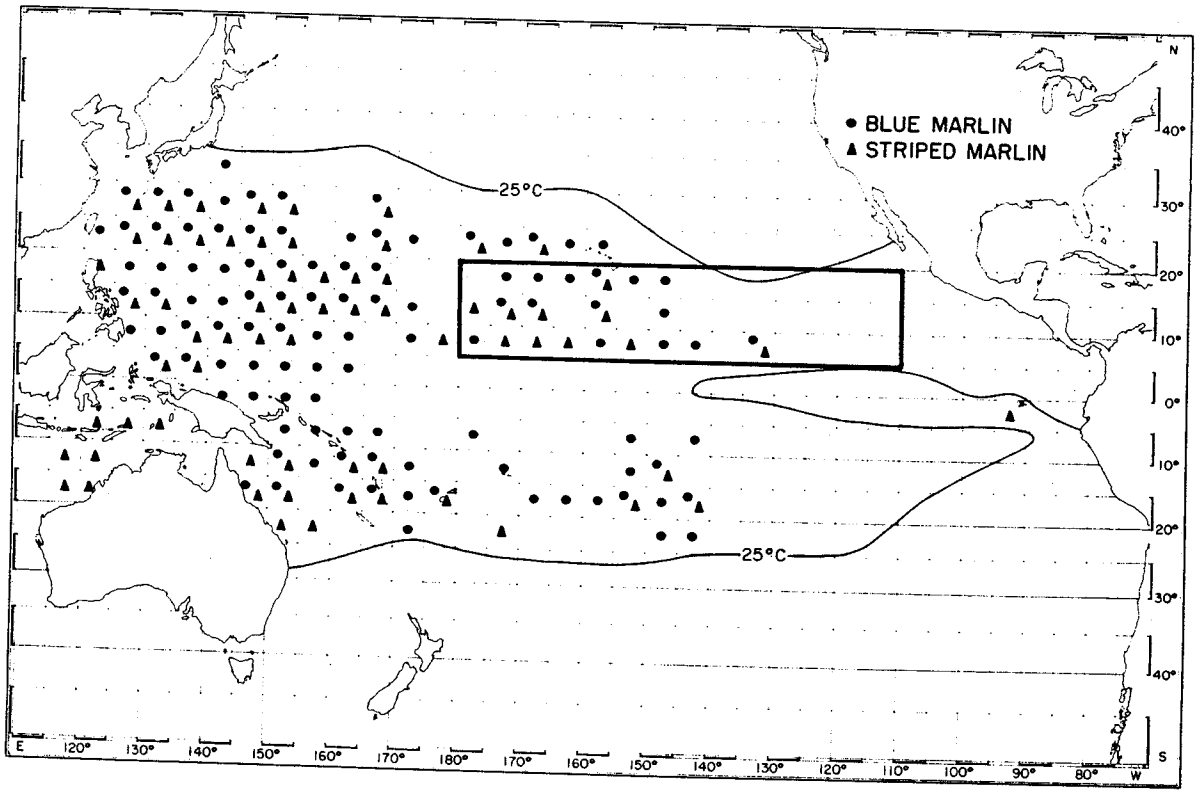

Figure 10.--Distribution of blue and striped marlin larvae in the Pacific Ocean (Matsumoto and Kazama 1974; Ueyanagi 1974; Nishikawa et al. 1978).

The distribution of blue and striped marlin larvae (Fig. 10) somewhat resembles that of the bigeye tuna larvae in the western and central Pacific. With the exception of two capture sites shown in the figure, none has been reported east of long. 140°W.

Information on the vertical distribution of tuna larvae has been obtained entirely from zooplankton and larval fish net tows. There is sufficient evidence to indicate that tuna larvae are distributed vertically to depths of 130 m or more (Strasburg 1960), but most are confined to the upper 50 or 60 m (Matsumoto 1958; Strasburg 1960; Klawe 1963; Ueyanagi 1969; Hirota 1977). Strasburg found no difference in the catches of tuna larvae made at the surface (horizontal net tows) and at 0-60 m (oblique net tows). Ueyanagi also found no difference in the catch rates of larvae sampled in horizontal tows made at the surface (0-2 m) and in subsurface (20-30 m) layers. This was also true for larvae of albacore, skipjack, yellowfin and bigeye tunas. No difference was apparent in the catch rates of Auxis and yellowfin tuna larvae taken in neuston net tows at the surface and in 1-75 m oblique bongo net tows, but much higher catch rates were obtained for skipjack tuna larvae at the surface than in the 1-75 m depth layer (Hirota 1977, tables 21-24).

There is some evidence of vertical diurnal migration by skipjack tuna larvae, but this may not be true of yellowfin and bigeye tuna larvae. Ueyanagi (1969) reported that the mean surface catch rate of skipjack tuna larvae per successful night tow was five times greater than that of day tows; whereas the mean catch rates of yellowfin and bigeye tuna larvae were about equal for day and night tows. Part of the higher night catches of skipjack tuna larvae could have been due to net dodging during daylight, but this effect should be small in view of the absence of similar day-night differences in the catch rates of yellowfin tuna and bigeye tuna larvae.

Food and Feeding

Adults

Tunas are broadly carnivorous, nonselective, opportunistic feeders, and will likely prey upon any forage organisms present in their vicinity. Studies of stomach contents of tunas in the eastern, central, and western Pacific (Reintjes and King 1953; Ronquillo 1953; King and Ikehara 1956; Watanabe 1958, 1960; Iversen 1962; Alverson 1963; Waldron and King 1963) all indicate that the diet of tunas is quite varied, but only a few kinds of the more abundant organisms present in a given area are taken in quantity.

The food of tunas consists of three major categories: crustaceans, molluscs (almost entirely cephalopods), and fish in varying proportions, depending upon the tuna species and the area in which they occur. In the central Pacific, fish and cephalopods make up the bulk of the food consumed. The proportions of the major food categories range from 1 to 6% crustaceans, 20 to 39% cephalopods, and 62 to 75% fish. In the eastern Pacific, however, crustaceans and fish are the major source of food, and cephalopods are only of minor importance. The proportions range from 45 to 59% crustaceans, 3 to 8% cephalopods, and 37 to 47% fish (King and Ikehara 1956; Iversen 1962; Alverson 1963; Waldron and King 1963).

The diversity of food eaten by tunas is reflected in the large number of invertebrate orders and fish families represented in the stomach contents. Among the crustaceans, food items consumed by yellowfin and skipjack tunas in the central and eastern Pacific included organisms in the Orders Isopoda, Amphipoda, Euphausiacea, Decapoda, Mysidacea, and Stomatopoda. Copepods were consumed only by skipjack tuna in the central Pacific, and bigeye tuna utilized the fewest crustacean Orders: Isopoda, Amphipoda, Euphausiacea, and Decapoda.

The greatest diversity in the food of tunas is in the large number of fish families represented. King and Ikehara (1956) list 47 fish families in the food eaten by yellowfin tuna and 35 fish families for bigeye tuna in the central Pacific, Alverson (1963) lists 22 fish families for skipjack tuna and 41 for yellowfin tuna in the eastern Pacific, and Waldron and King (1963) list 41 fish families for skipjack tuna in the central Pacific. Of the total fish families given for each tuna species, 14 were common to all four species, 22 were common to bigeye, yellowfin, and skipjack tunas in the central Pacific, 33 were common to bigeye and yellowfin tunas in the central Pacific, and 13 were common to yellowfin and skipjack tunas in the eastern Pacific.

Despite the diversity of the fish species eaten by the tunas, fish of only a few families make up the bulk of the fish portion of the diet, and the major fish families differed for some species by area. In the central Pacific, the Families Scombridae, Gempylidae, and Bramidae were the most important fish food items of yellowfin and bigeye tunas and Scombridae, Carangidae, and Mullidae of skipjack tuna. In the eastern Pacific, the fishes of the Families Scombridae, Ostraciidae, Tetraodontidae, and Exocoetidae were important food items for the yellowfin tuna and those of Gonostomatidae, Exocoetidae, Trichiuridae, Myctophidae, and Engraulidae were important food items of skipjack tuna. Other studies by Ronquillo (1953) and Watanabe (1958) show similar diversity and similarities in fish families represented in the stomach contents of tunas from the western equatorial Pacific.

Tunas feed primarily during the hours of daylight from the surface to depths of 380 m (Saito 1973; Saito and Sasaki 1974). Feeding at the surface usually occurs in compact schools, consisting of fish that are generally smaller than 100 cm. These schools are often composed of mixed species, such as skipjack tuna with small yellowfin tuna, small yellowfin tuna with small bigeye tuna, or all three species together, and are generally encountered in the vicinity of land masses, seamounts, banks, or around floating objects (Alverson and Peterson 1963). The larger yellowfin and bigeye tunas feed at great depths (135 m or more), but may ascend to shallower waters to feed at night (Watanabe 1958).

The marlins also are carnivorous opportunistic feeders and feed on pelagic fish, squid, and crustaceans. Members of six orders of invertebrates (Decapoda, Amphipoda, Stomatopoda, Heteropoda, Pteropoda, and Cephalopoda) and 36 fish families have been reported from stomachs of 6 species of billfishes from the western Pacific (Watanabe 1960). Although the list of food items may not be representative of any single species, (all items were listed under marlin), it does indicate that the variety of food items eaten by billfishes as a group is comparable to that of tunas. Strasburg (1970) indicated that the dietary habits of marlins varied between species and areas. He found that the striped marlin fed mostly on

squids, sauries, and other fishes off New Zealand, sauries off California, squids off Peru and Chile, anchovies off northern Chile, snake mackerel and lancetfish off the Bonin Islands, and tunas in the central Pacific. The blue marlin fed mostly on squids in the Philippine Sea, tunalike fish off New Zealand and in the central Pacific, dolphin and tunalike fish off the Bahamas, and small tunas (young albacore; frigate tuna, Auxis thazard; and kawakawa, Euthynnus affinis) in Hawaii. Other fishes consumed by striped marlin include mackerels, carangids, sardines, herring, cornetfishes, and boxfishes (Ueyanagi and Wares 1975).

Larvae and Juveniles

There is only limited information on the food organisms consumed by tuna and billfish larvae. Studies of stomach contents provide only a partial list of the food eaten, since much of the delicate food items presumed to comprise the diet of the larvae quickly become unrecognizable due to digestion. Nishikawa (1975) noted only small numbers of copepods and residues of fish larvae and crustaceans in the stomachs of skipjack tuna larvae (3-9.5 mm standard length (SL)), and fish larvae, Euphausia, larval Decapoda, Amphipoda, and Octopoda in stomachs of skipjack tuna juveniles (17.5-26.0 mm SL). Lipskaya and Gorbunova (1977) recorded 4 kinds of copepods and larvae of 2 kinds of flyingfish in stomachs of striped marlin larvae and juveniles (6.4-29.0 mm SL), and 7-9 different species of copepods and larvae of 12-15 fish species, including those of the Families Istiophoridae, Gempylidae, Scombridae, Coryphaenidae, Holocentridae, Mullidae, Myctophidae, Engraulidae, and Exocoetidae, in the stomachs of blue marlin larvae and juveniles (6.0-22.0 mm SL).

Uotani et al. (1981) examined stomach contents of numerous (>4,000) larvae of albacore, yellowfin, bigeye, southern bluefin, Thunnus maccoyii, skipjack, and frigate tunas, ranging from 2.21 to 22.5 mm total length (TL), from the area northwest of Australia. They recorded 10 species of copepods, copepod nauplius and eggs, Ostracoda, 1 species of Cladocera, and other Crustacea; polychaete larvae; fish larvae; arrow-worm; and Appendicularia. The stomach contents of four species of tunas (albacore, yellowfin, bigeye, and southern bluefin) consisted mainly of small items 0.21-0.80 mm body length, but that of skipjack and frigate tunas contained numerous items exceeding 0.81 mm body length. Feeding studies of larval fish such as herring (Blaxter 1965; Bjoerke 1978; Uotani et al. 1978) and anchovy (Ciechomski 1967b; Lasker 1975), show that the diet at initial feeding consists largely of mollusc larvae, and copepod eggs and nauplii. Other crustacean larvae such as the nauplii of barnacles, mollusc larvae that generally hatch as trochophores, trochophores of sabellid polychaete and larvae of echinoderms all may serve as initial food of fish larvae (May 1970). It is conceivable that larvae of tunas and billfishes also utilize similar food items at first feeding, as evidenced by the copepod nauplii found by Uotani et al. (1981) and by the successful experimental rearing in tanks of various tuna larvae that had been initially fed rotifers or oyster larvae (Harada et al. 1971; Harada, Murata, and Furutani 1973; Harada, Murata, and Miyashita 1973; Harada et al. 1980).

Although larvae of tunas and billfishes may require delicate food items at initial feeding, their dependence on such food may be for a brief period only. The unusually large mouth of these larvae, which is approximately 20 to 32% of body length in larvae larger than about 4.0 mm (Gorbunova 1975, figures from Ueyanagi 1963) permits them to feed on fish larvae and other larger organisms much sooner than larvae of other fishes.

Vision is the most important sensory function used in feeding by marine fishes. For successful feeding and survival, the larvae must perceive the prey. Studies on visual perception by larvae indicate that first-feeding larvae of herring, plaice, pilchard, and anchovy, which all have rather small eyes, react to prey at distances of 0.2-1.0 body length, and that the perceptive range increases with growth (Hunter 1980). Similar observations have not been made for tuna or billfish larvae, but their proportionately larger eyes, which range from 10 to 15% of body length in larvae 3.2-16.5 mm SL (Gorbunova 1975), should enable them to perceive prey at greater distances. Other tests measuring thresholds of light intensity for larvae and juveniles of several species of salmon, whitefish, pike, herring, and plaice indicate a falloff in the rate of feeding corresponding with light conditions at dusk and dawn (Blaxter 1969). The daily feeding period thus must vary considerably with season, latitude, clarity of water, and cloud cover for these fish, and this should apply to tuna and billfish larvae as well.

Spawning

Spawning by tunas and billfishes have been determined from examination of gonads and from the capture of larvae. Figures 7-10 show the maximum area in which spawning has occurred in the Pacific Ocean, based on the capture of larvae. Spawning by tunas and billfishes generally occur throughout the year in tropical waters and during the summer at higher latitudes. Consequently, seasonal variations are evident mainly at the northern and southern extremeties of the spawning area.

In the western Pacific, spawning by yellowfin and bigeye tunas occurs between lat. 20°N and the Equator in the first quarter of the year, between lat. 30°N and 10°S in the second quarter, between lat. 35° and 15°N in the third quarter, and between lat. 15°N and 20°S in the fourth quarter (Nishikawa et al. 1978). In the central Pacific (long. 140°W to 180°), yellowfin tuna spawn throughout the year between lat. 14°N and 5°S and in the first quarter between lat. 6° and 14°S (Matsumoto 1958). In the eastern Pacific yellowfin tuna spawn throughout the year between lat. 25° and 7°N (Klawe 1963). The annual spawning potential of yellowfin tuna has been estimated, on the basis of gonad indices (Kikawa 1966), as being slightly greater in the central and eastern equatorial Pacific than in the western Pacific, and that of bigeye tuna between long. 100° and 140°W as being double that in the western Pacific west of the 180th meridian.

Skipjack tuna also spawn across the entire Pacific but spawning intensity is sharply reduced in the eastern equatorial Pacific east of long. 120°W (Klawe 1963). Most of the spawning by skipjack tuna occurs in equatorial waters between lat. 10°N and 10°S, and long. 130° to 145°W, and between lat. 20°N and 10°S from long. 145°W to the Asian Continent. The center of highest spawning lies between long. 140°W and 160°E (Matsumoto 1975). Other spawning areas north of lat. 20°N include the waters around the Hawaiian Islands (Seckel 1972) and south of Japan between lat. 25° and 30°N (Ueyanagi 1969). As in yellowfin and bigeye tunas, spawning occurs throughout the year in equatorial waters and during summer at higher latitudes.

Tunas spawn in a fairly wide range of temperatures, varying by species and locality. In the western Pacific, yellowfin tuna spawn in temperatures between 24° and 29°C; bigeye tuna, between 27° and 29°C; and skipjack tuna, between 23.5° and 30°C (Ueyanagi 1969). In the eastern Pacific, the

temperature range of yellowfin tuna spawning is between 24° and 32°C, with a marked increase in spawning as the temperature increases above 26° or 27°C (Klawe et al. 1970). The spawning temperatures in the central Pacific around the Hawaiian Islands range from 21.7° to 27°C for yellowfin tuna (unpublished data, Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service) and 22° to 27°C for skipjack tuna (Matsumoto et al. 1984). The lower end of the temperature range for yellowfin tuna in Hawaiian waters appears to be close to the minimum spawning temperature for this species. Harada et al. (1978) reported that no normal yellowfin tuna larvae hatched at temperatures of 17.2°-20.8°C during laboratory rearing experiments.

The known spawning areas for striped and blue marlins are indicated in Figure 10. The nearly complete absence of billfish larvae in equatorial waters east of long. 130°W may be due to the absence of larval studies of these fishes from that area. A report on the sexual maturity of billfish caught in this area (Kume and Joseph 1969) shows that females of both striped and blue marlins in spawning condition were present in the area bounded by lat. 20°N and 30°S, and long. 110° and 130°W, with the southern distribution limited to the lower latitudes (10°S) east of long. 110°W. As in the tunas, spawning presumably occurs throughout the year along the Equator and during summer, north and south of the Equator.

In all the species mentioned above, the mature female releases large numbers of eggs in a single spawning. The estimates for bigeye tuna ranged from 2.9 to 6.3 million eggs (Yuen 1955); for yellowfin tuna, 2 to 8 million eggs (June 1953); for skipjack tuna, 0.1 to 2 million eggs (Yoshida 1966); and for striped marlin, 11 to 29 million eggs (Eldridge and Wares 1974). No information is available on the fecundity of blue marlin.

Spawning by tuna in captivity has been reported by Kaya et al. (1982). Female skipjack tuna weighing between 1.4 and 2.2 kg spawned in a tank within 8 h after capture. The spawned ova measured 1.0 mm, the same as a ripe ova, as compared with ovarian ova of 0.59-0.74 mm in fish taken from the same school. The rapid development of the ova--normal development is estimated at 2-3 months (Matsumoto et al. 1984)--was believed to have been induced by stresses experienced by the fish during the capture, transport, and confinement processes. The viability of the ova was demonstrated by artificial fertilization and successful hatching of the larvae. The rapid maturation and spawning of skipjack tuna in captivity is currently being exploited to produce larval skipjack tuna for experimental studies.

Development and Growth of Larvae

A number of tuna species have been reared successfully from artificially fertilized eggs. These include yellowfin tuna (Harada et al. 1971, 1980), and skipjack tuna (Inoue et al. 1974; Ueyanagi et al. 1974), and also bullet tuna, *Auxis rochei* (= *A. tapeinosoma*; Harada, Murata, and Furutani 1973), frigate tuna, *A. thazard* (Harada, Murata, and Miyashita 1973), and striped bonito, *Sarda orientalis* (Harada et al. 1974), which are of minor commercial importance.

Yellowfin and skipjack tuna embryos developed and hatched in 23 to 35 h after fertilization in water temperatures of 24.5°-29°C; whereas those of bullet and frigate tunas and striped bonito developed and hatched in 34 to 72 h in water temperatures of 20°-24°C. Yellowfin and skipjack tuna larvae

were 2.6-2.7 mm TL at hatching, bullet and frigate tunas 3.3-3.6 mm TL, and striped bonito 4.1-4.3 mm TL. As in other fishes (Ciechomski 1967a; Fonds et al. 1974), the rate of embryonic development increased with temperature. The yolk was absorbed 2 days after hatching in striped bonito and skipjack tuna, in 3 days in yellowfin tuna, and from 2 to 4 days in mackerel tuna. The eyes were completely pigmented, the mouth was fully formed, and feeding began at the time of yolk absorption.

Feeding by tuna larvae reared in tanks started 2-3 days after hatching, at about the time of yolk absorption. The initial food of yellowfin tuna larvae consisted of rotifers, Branchionus plicatilis, and oyster larvae, Crasostrea nippona (Harada et al. 1971). The larvae were fed several kinds of marine copepods (unspecified species) 8 days after hatching when they were 5-6 mm TL. In one feeding study (Harada et al. 1980), yellowfin tuna larvae were fed a diet of rotifers, copepods, and larvae of parrotfish, Oplegnathus fasciatus, 2.5-4.0 mm TL. Due largely to feeding on fish larvae, larval growth was found to be especially rapid after the 10th day. In examining stomach contents of larval and juvenile skipjack tuna taken in plankton nets, Nishikawa (1975) noted that of 15 larvae with identifiable food remains, 5 larvae (3.0 to 9.2 mm TL) had consumed copepods and 1 larva (7.0 mm TL) had eaten a fish larva; that most (73%) of the juveniles (17.5-26.0 mm TL) had consumed fish larvae, whereas others had consumed euphausiids, copepods, decapods, amphipods, and octopods; and that juveniles, 48.0-120 mm, fed almost entirely on fish larvae. Based on these studies, it appears that larval tunas begin feeding on copepods at about 3.7 mm body length and continue to do so until they are at least 26 mm in body length; larval fish appear in their diet at about 6 or 7 mm TL or approximately 10 days after hatching; and fish larvae and euphausiids are the dominant food items in juveniles 17 to 26 mm in TL. Similarly, stomach content analyses by Lipskaya and Gorbunova (1977) and Gorbunova and Lipskaya (1975) indicate that billfish larvae initially feed on copepods and feed on fish larvae when they are about 6 mm TL.

Growth was extremely rapid for larvae of all species from about the 10th day. A 10-day-old yellowfin tuna larva grew from 5.8 to 51 mm in 28 days (indicating a linear growth rate of 1.6 mm/day), in water temperatures declining from 28.6° to 25.6°C. The total growth was from 2.7 mm at hatching to 51 mm in 38 days. Bullet and frigate tunas grew even faster, 3.2-3.5 mm/day in temperatures rising from 25.4° to 28.3°C. Frigate tuna grew from 3.3 mm at hatching to 120 mm in 33 days, and bullet tuna from 3.3 to 157 mm in 52 days. Striped bonito showed the fastest growth rate, 6.4 mm/day from the 10th to 42d day, in temperatures increasing from about 20° to 28°C. The total growth was from 4.1 mm at hatching to 290 mm in 99 days. Fonds et al. (1974) indicated that the growth rate of garfish, Belone belone, larvae was linearly correlated with temperature. If this holds for tuna larvae as well, the growth rate of yellowfin tuna larvae should have been greater than reported above. Growth of skipjack tuna larvae is not known since larvae of this species have not been reared beyond 5 days.

THE DEEP OCEAN MINING ENVIRONMENTAL STUDY (DOMES) AREA

Environment

Oceanographic Features

The premining environmental conditions in the DOMES area have been summarized by Ozturgut et al. (1978). Some oceanographic features that affect the tuna and billfish, particularly the eggs and larvae, are worth noting. Several surface currents prevail in the area: the westward flowing North Equatorial Current (NEC) between about lat. 20° and 10°N, an eastward flowing North Equatorial Countercurrent (NECC) between lat. 10° and 4°N, and a westward flowing South Equatorial Current (SEC) between lat. 4°N and 9°S (Fig. 11). The position and velocity of these currents vary seasonally. Measurements of the currents at Sites A, B, and C (Halpern 1976, 1977) indicate an eastward flow at Site A with a mean velocity of almost 20 cm/s (9.4 nmi/day) at a depth of 20 m in the fall, an eastward flow at Site B with a mean velocity of 3 cm/s (1.3 nmi/day) in the spring, and a westward flow at Site C with a mean velocity of almost 17 cm/s (7.9 nmi/day) at 20 m in the fall. Seasonally the NECC fluctuates in velocity from 5 to 30 cm/s (2.4 to 14.1 nmi/day) in the spring to 5 to 15 cm/s (2.4 to 7.1 nmi/day) in the fall (NOAA 1981). The effects of these currents on tuna are discussed under Movement of Tunas.

Surface temperatures (LaViolette and Seim 1969) vary noticeably in the DOMES area. At the longitude through Site C, the mean surface temperature at lat. 20°N varies from 21° to 24°C during the year. At the longitude through Site B, the temperature during the year varies from 23° to 25°C and from 22° to 26°C, at Site C. The 25°C isotherm, which roughly defines the

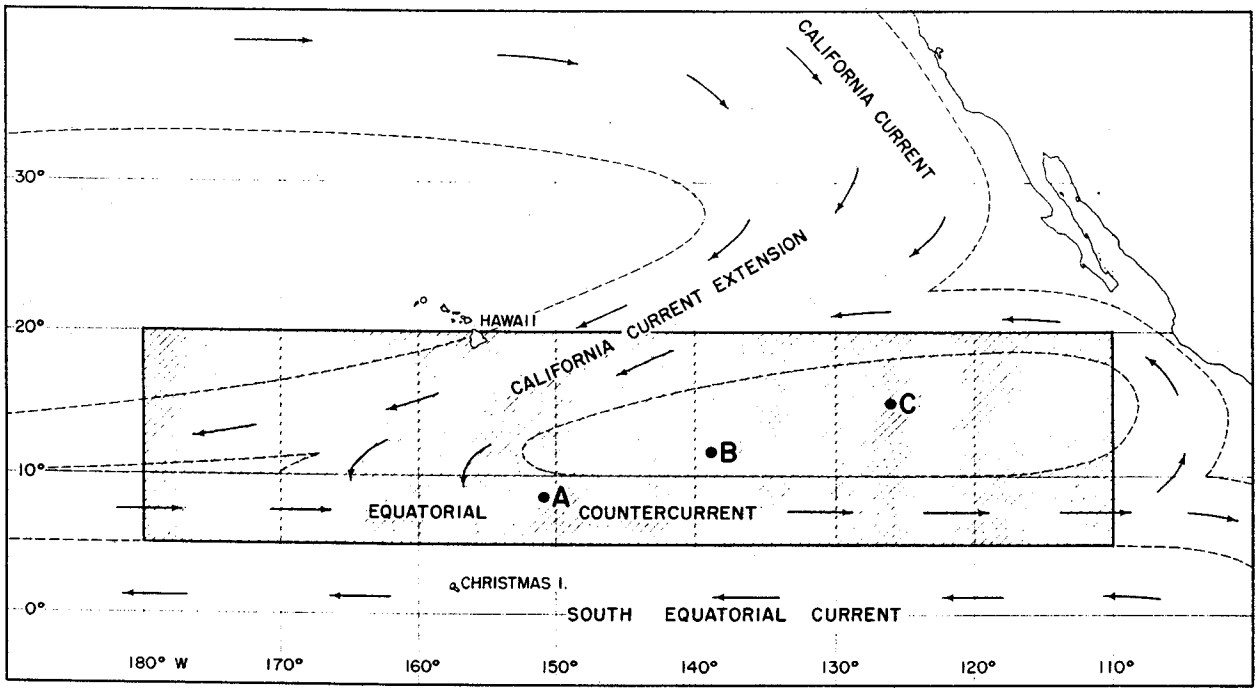

Figure 11.--General surface circulation scheme in the eastern tropical Pacific with prime manganese nodule mining area (hatched) and DOMES stations A, B, and C.

limit of larval capture, lies to the north of Sites A and B during the entire year, but only for 6 months at Site C. The thermal structure in the DOMES area is typical of the tropical Pacific with a well-defined surface mixed layer overlying a strong thermocline (Fig. 12). The mean depth of the mixed layer was 35±32 m during summer and 55±18 during winter (Ozturgut et al. 1978).

Measurements of suspended particulate matter (SPM) in the DOMES region made during the summer of 1975 indicate that SPM is most abundant in surface waters (mean concentration of 42±20 μg/ℓ), and uniformly low, 10±3 μg/ℓ, below 200 m (Baker et al. 1979). The concentration in surface waters is considered low but typical of open ocean waters. The general features of SPM concentrations change very little between summer and winter. Most of the particles (91±2.9%) are smaller than 4 μm with mean medium diameters of 2.0±0.4 μm.

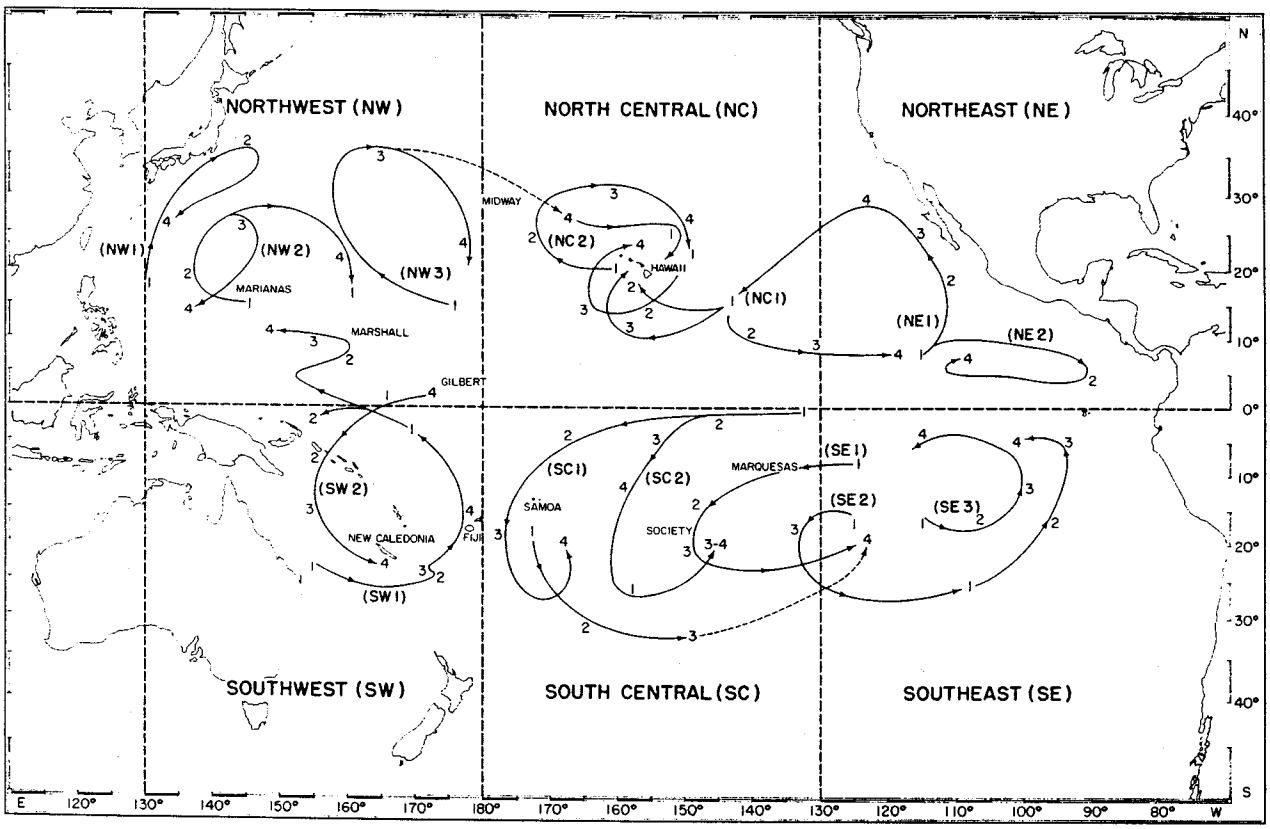

Figure 12.--Assumed movement of the various stocks of skipjack tuna in the Pacific Ocean. The numerals along the migratory routes represent quarters and locations of high CPUE cells of skipjack tuna taken by the Japanese tuna longline fishery, 1964-67. Stock designations are shown in parentheses (Matsumoto 1975).

Biological Features

Zooplankton research in the DOMES area at Sites A, B, and C was done in the summer of 1975 and winter of 1976 (Hirota 1977). Information on microzooplankton was limited to vertical distribution. The major features of distribution of microzooplankton (0.183-0.035 mm diameter) were: (1) nauplii, tintinnids, and *Microsetella* (copepod) tended to have maxima shallower than 40-60 m; (2) *Oncaea* (copepod) tended to have a much deeper

maximum, often at 100 m or more; and (3) radiolaria and foraminifera showed relatively smaller depth variation than (1) or (2) above. The nauplii, tintinnids, and Microsetella were the most likely to be associated with the chlorophyll maximum, which occurred at depths of 69±24 m in summer and 54±30 m in winter. The approximate ranges of numerical abundance of each of the five taxa were 3,000-15,000/m^3 for nauplii, 1,000-15,000/m^3 for tintinnids, 1,000-10,000/m^3 for radiolarians and foraminifers, 500-5,000/m^3 for Oncaea, and 100-500/m^3 for Microsetella. The abundance estimates were about a third of those in the eastern Pacific (EASTROPAC) area (Beers and Stewart 1971) and overlapped those in Hawaiian waters (Gundersen et al. 1976). The average abundance of microzooplankton smaller than 0.035 mm in the upper 160 m was 145/ℓ of ciliates and 5/ℓ of copepod nauplii and foraminifers. The microplankton standing stock as "tissue volumes" integrated over the 0-150 m layer showed a range of 423-852 mm^3/m^2. These volumes were approximately one-half of the volumes reported for Hawaiian waters (Gundersen et al. 1976) and one-third of those for the EASTROPAC area along long. 105°W (Beers and Stewart 1971).

The average macrozooplankton standing stocks (dry weight) integrated over the 0-200 m depth layer ranged from 1,048 to 2,900 mg/m^2 at the three site stations (Hirota 1977). The highest concentrations of macrozooplankton were in the upper 150 m and moderate concentrations between 200 and 900 m. The areal distribution of the standing stocks (neuston net catches) showed a gradient from southeast to northwest, approximately normal to the DOMES station sites. The highest stocks were at the southern half of Sites B and C and the lowest along Site A and the top half of Site C.

The major taxa of macrozooplankton were copepods, euphausiids, chaetognaths, larvaceans, ostracods, pteropods, and larval fishes (Hirota 1977). The mean abundance of copepods in the upper 100 m ranged from 152,000/1,000 m^3 at Site A to 296,000/1,000 m^3 at Site B in 1975, and 171,000/1,000 m^3 at Site A to 205,000/1,000 m^3 at Site C in 1976. The most common species were the small (ca. 1 mm TL) cyclopoids (Oncaea and Oithona) and calanoids (Paracalanus, Calocalanus, and Clausocalanus), whose abundances ranged from 1,000 to 59,000/1,000 m^3. The main abundance of euphausiids in the neuston layer ranged from 1,400/1,000 m^3 at Site A to 2,900/1,000 m^3 at Site B. Both copepods and euphausiids were most abundant at Site B; whereas copepods were nearly equally abundant at Sites A and C, and euphausiids least abundant at Site A.

The mean abundance of larvaceans ranged from 18,000 to 250,000/1,000 m^3 in the neuston layer and 20,000 to 33,000/1,000 m^3 in the 0- to 200-m depth layer (Hirota 1977). Corresponding values for pteropods were 3,000-16,000/1,000 m^3 and 2,000-5,000/1,000 m^3, and 200-1,500/1,000 m^3 and 5,000-18,000/1,000 m^3 for ostracods in the two depth layers. The mean abundance of chaetognaths ranged from 2,000 to 9,000/1,000 m^3. Large differences in abundance were noted between sites and years.

Fish larvae from the neuston layer were predominantly Hemiramphidae and Exocoetidae with a few midwater forms, mainly Gonostomatidae, and a number of nearsurface fish (Carangidae, Scombridae, Bramidae, and Scomberesocidae). Larvae from the 0- to 100-m depth layer included mainly midwater forms (Gonostomatidae and Myctophidae) and low concentrations of nearsurface fish (Scombridae, Coryphaenidae, Hemiramphidae, and Exocoetidae). Three taxa, Hemiramphidae, Exocoetidae, and Gonostomatidae, were abundant at all sites whereas Scombridae were well represented at Site

A, Carangidae and Bramidae at Site B, and Scomberesocidae at Site C. The mean abundance of all fish larvae in the 0- to 100-m depth layer ranged from 700 to 900/1,000 m^3 in 1975 and from 300 to 400/1,000 m^3 in 1976. The families of commercial interest included the Scombridae (tunas and mackerels) and Istiophoridae (billfishes), the latter represented by a single specimen taken at Site A (Hirota 1977).

Tunas and Billfishes in the DOMES Area

Information on fishes in the DOMES area has been reviewed by Blackburn (1976). Commercial fisheries in the area exist for yellowfin, bigeye, and skipjack tunas and striped and blue marlins. Other billfishes taken in small quantities include the sailfish, Istiophorus platypterus, shortbill spearfish, Tetrapturus angustirostris, and black marlin, Makaira indica. There are five commercial fisheries for tunas or billfishes in the area: (1) the Japanese longline fishery, which fishes throughout the area with the exception of the northeastern corner (lat. 10°-15°N, long. 115°-130°W); (2) the Japanese live-bait and purse seine fisheries for skipjack and small yellowfin tunas in the South Pacific, which in recent years (particularly the purse seiners) have extended eastward along the Equatorial Countercurrent to long. 169°W (Tanaka 1978); (3) the United States live-bait and purse seine fisheries for skipjack and small yellowfin tunas, which in recent years (particularly by the seiners) have expanded westward to long. 150°W between lat. 15°N and 5°S (Matsumoto et al. 1984); (4) the Hawaiian live-bait fishery for skipjack tuna, which fishes at or just outside the northern edge of the DOMES area; and (5) the Hawaiian longline fishery for yellowfin and bigeye tunas and billfishes. The DOMES area commercial catches in metric tons (MT) in 1973 (Blackburn 1976) were approximately:

Yellowfin tuna	62,700 MT	(57,400 MT United States purse seine and longline; 5,300 MT Japanese longline)
Bigeye tuna	16,600 MT	(Japanese longline)
Billfishes	5,500 MT	(Japanese longline)
Bigeye tuna and billfishes	300 MT	(Hawaiian longline)
Skipjack tuna	6,700 MT	(United States purse seine and live bait)
Total	91,800 MT	

The total catch would be much greater today if the Japanese skipjack tuna catch east of the 180th meridian--the eastward expansion to long. 160°-165°W began in 1977 (Tanaka 1978)--and the catch of the Hawaiian recreational fishery were included. Catches of both the Japanese skipjack tuna fishery and the Hawaiian recreational fishery in the DOMES area are not readily available; however, it was estimated (Honolulu Laboratory staff) that the latter caught 996 MT of billfishes and 2,501 MT of tunas, mostly yellowfin and skipjack, in 1976.

Larvae of yellowfin, bigeye, and skipjack tunas and striped and blue marlins are generally present in the DOMES area (Figs. 7-10). Also present are larvae of species of fish taken in smaller quantities, i.e., frigate tuna, sailfish, and shortbill spearfish. Larvae of yellowfin and skipjack

tunas are most abundant around Hawaii in summer and absent in winter. In other sectors of the DOMES area north of lat. 15°N, larval abundance is also seasonal. In the sector west of long. 150°W between lat. 14° and 5°N, larvae are abundant throughout the year and their abundance peaks during winter (Matsumoto 1958). Between long. 150° and 130°W, larvae of yellowfin tuna are generally restricted to south of lat. 10°N. This is more pronounced for skipjack tuna larvae (Fig. 9). As mentioned previously, the dip in the distribution to lat. 10°N in this sector may be due to a similar southward shift of the surface isotherms, but it is also due partly to the low level of sampling north of lat. 10°N. East of long. 130°W, larvae of yellowfin tuna are taken as far north as lat. 20°N during summer (Matsumoto 1958; Strasburg 1960; Klawe 1963), but larvae of skipjack tuna occur only occasionally and in small numbers (Klawe 1963). Larvae of bigeye tuna occur in a similar manner as those of yellowfin tuna but at lower levels of abundance. In Hawaii and the equatorial Pacific, including the DOMES area, skipjack tuna larvae are the most abundant: the catches are twofold to threefold greater than that of yellowfin tuna larvae (Matsumoto 1958; Higgins 1970).

Larvae of striped and blue marlins are found throughout the north-south range of the DOMES area west of long. 145°W (Fig. 10). The apparent absence of larvae east of long. 145°W may be the result of low priority given to studies of billfish larvae in that region. Although detailed studies of larval fish in the EASTROPAC area have been made (Ahlstrom 1971, 1972), the studies were based solely on collections obtained from oblique hauls to 200 m. Collections obtained from surface hauls, which produce the most larval billfish, have not been analyzed. Thus far, larvae of only one species of lesser commercial importance, shortbill spearfish, have been taken at one station in the DOMES area at approximately lat. 19°N, long. 137°W (Howard and Ueyanagi 1965).

Movement of Tunas

Hypotheses and observations on tuna movement in this region include those of Rothschild (1965), Blackburn and Laurs (1972), Seckel (1972), Williams (1972), and Matsumoto (1975). These authors variously stressed the probable importance of food sources, ocean currents, and temperature in the migratory behavior of skipjack tuna.

It is generally accepted that tunas, mainly skipjack, migrate eastward from the eastern half of the DOMES area along the NECC. These fish enter the eastern Pacific northern fishery off central Mexico in the spring, proceed northward along Baja California as the season progresses, and return south along the coast in the fall. The major portion of the fish return to the equatorial central Pacific to spawn (Fink and Bayliff 1970).

Williams (1972) proposed three migration models involving the movement of larvae, young and adult skipjack tuna from the equatorial Pacific west of long. 130°W to the eastern Pacific northern fishery in spring and their return to the central Pacific at the end of the season. According to the model, the NECC provides the eastward transport of larvae and young, and the California Current Extension provides transport for their return as adults to the equatorial spawning grounds west of long. 130°W. Matsumoto (1975) proposed the existence of a number of semi-independent skipjack tuna stocks in the Pacific Ocean by following the quarterly movement of the areas of high catch rates in the Japanese longline fishery over a period of 4 years

(1964-67). He recognized approximately seven stocks in each hemisphere (Northern and Southern), with the migratory paths of the stocks following a clockwise direction in the central and western North Pacific and a counterclockwise direction in the eastern North Pacific and Southern Hemisphere, corresponding with the surface current flow of the major water masses (Fig. 12). Matsumoto further attempted to fit the assumed routes taken by skipjack tuna tagged in the eastern Pacific and captured in Hawaii and Christmas Island by projecting the duration of liberty of these fish to the time scale and direction of movement indicated in the proposed model (Fig. 13, primary and assumed secondary routes). The most likely paths all pass through the DOMES area.

EFFECTS OF MINING

Impact on Environment

Most of the concern on seabed mining relates to the surface and benthic discharges and their possible effects on the biota. Investigations on the discharge and surface plume resulting from test mining operations indicated that the discharge consisted of sediment, bottom water, nodule fragments, and benthic biota. Sediment was the major component of the particulates discharged, of which 68-87% by weight was pelagic clay, and the residual was primarily calcium carbonate, sea salt, and silicon dioxide (Bischoff et al. 1979; Ozturgut, Lavelle, and Erickson 1981). Measurements of the discharge were made during mining tests conducted by Ocean Mining Associates (OMA) and Ocean Management, Inc. (OMI). In the OMA tests, the total particulate concentration in the shipboard discharge averaged 5.8 g/ℓ. The discharge passed over the side, fell to the sea, and mixed rapidly with the surface water. A large percentage of the sediment particulates were found to settle out of the euphotic zone within a few hours, but the fine fraction of the discharge was presumed to be long-lived in the mixed layer. The maximum near surface concentration of particulates at the transect closest to the mining ship (15 min after initial mixing or 75 m behind the ship) was 900 μg/ℓ (Ozturgut et al. 1980). The particulate concentrations in the mixed layer averaged 443 μg/ℓ after 1 h, 177 μg/ℓ after 2 h, and 69 μg/ℓ after 3 h, with ambient concentration being 28.5 μg/ℓ. In the OMI tests, the particulate concentrations were 598 μg/ℓ after 1 h, 55 μg/ℓ after 5 h, 45 μg/ℓ after 28 h, and 34 μg/ℓ after 37 h, and the ambient concentration was 37 μg/ℓ (Lavelle et al. 1982). The surface plume measured during the OMI tests (Burns et al. 1980), had traveled about 4.5 km from the mining ship in <5 h and was 1 km wide at that point (Fig. 14).

During full-scale commercial mining, the miner will discharge three times the volume of the test miner and at higher bulk densities, but the mining ship speed (estimated at 1 m/s) will be four times that of the average test miner speed, so that discharge volumes per unit ocean area will be slightly decreased over that of the mining tests (Lavelle and Ozturgut 1981).

The pattern that commercial mining ships make across a mining area will be one that maximizes the sea floor recovery of nodules. Thus Lavelle and Ozturgut (1981) envision that 30- by 30-km mining tracts will be successfully and intensively mined, and that within this area, the mining ship will traverse a rectangular pattern 30 km on the long side and 3.6 km on the shorter side, with such rectangular patterns offset by 40 m. Taking

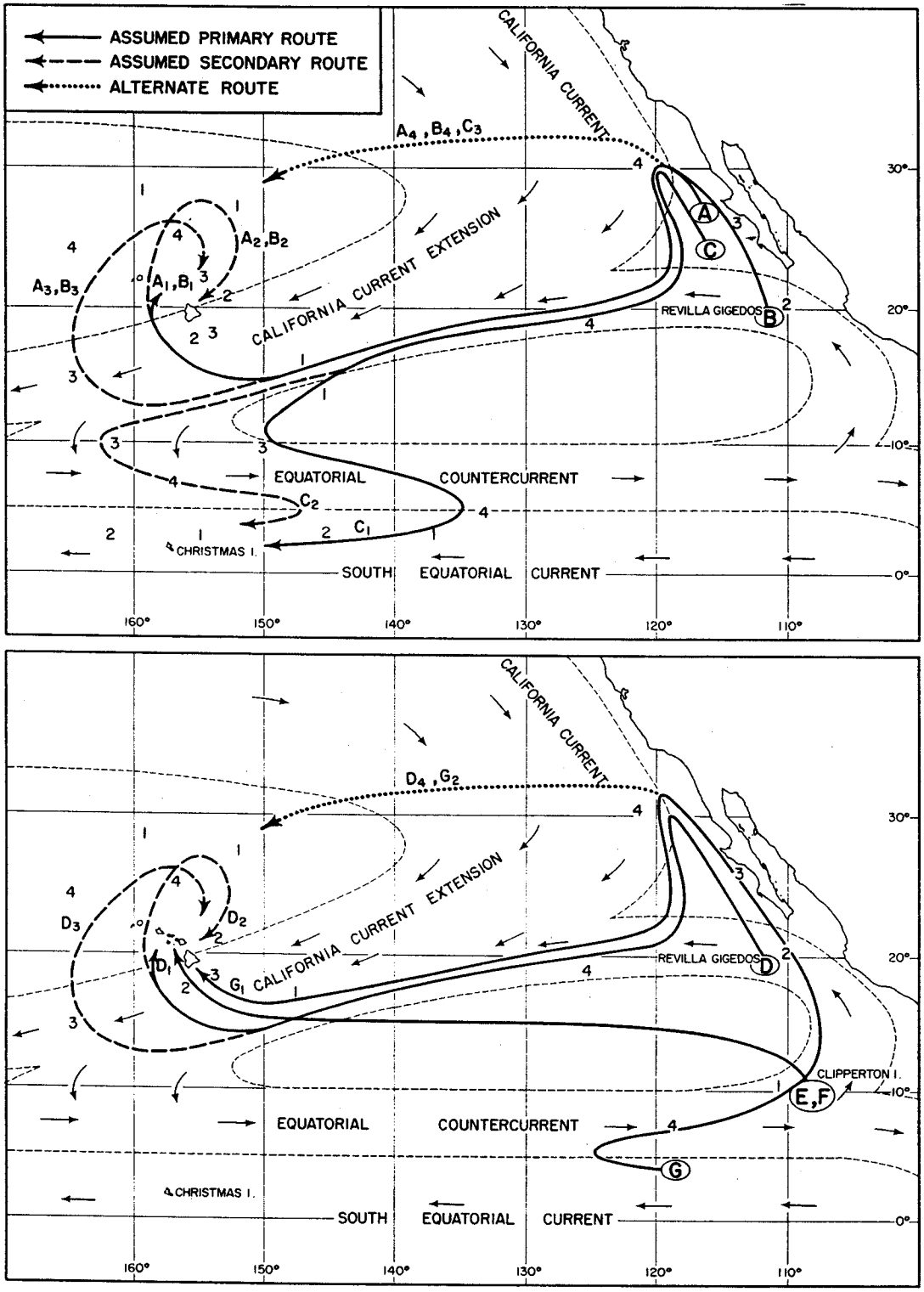

Figure 13.--Assumed routes followed by tagged skipjack tuna from the eastern to the central Pacific. The letters represent tagged fish and the numerals along the routes represent quarters of high catch rates of skipjack tuna taken by the Japanese tuna longline fishery, 1964-67 (Matsumoto 1975).

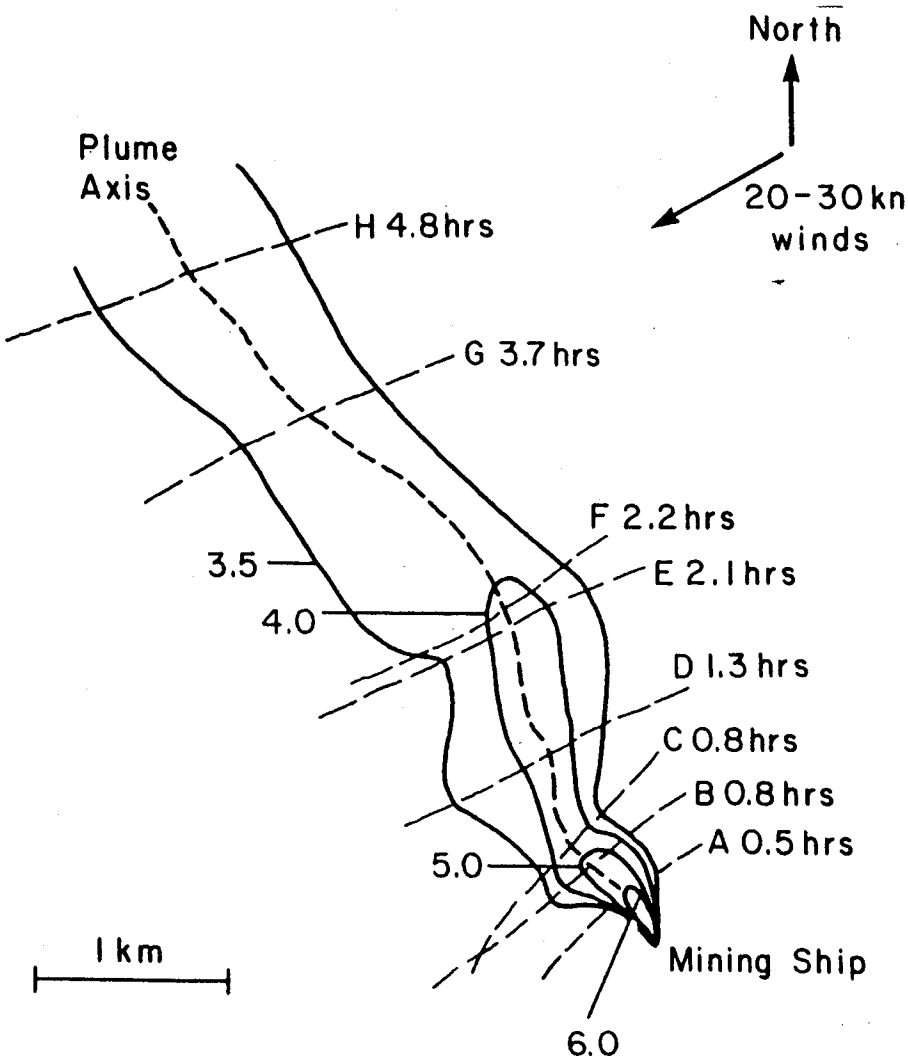

Figure 14.--Planar view of the plume reconstructed from nephelometer traces. Contour levels are nephelometer voltages. Background voltage is approximately 3.3 (Burns et al. 1980).

the long axis to be normal to the advection stream and 1 m/s as the speed of the mining ship, the authors envision traverses resulting in a serpentine surface plume approximately 70 km long (Fig. 15). Based on their models describing the dispersion of particulates, concentrations higher than 100 μg/ℓ would be found at distances <6 km downstream of the mining ship and concentrations of 50 μg/ℓ (near ambient) at distances of about 14 km.

Suspended particulates were found to significantly reduce light penetration. At depths between 10 and 20 m in 1-h-old plume water, the attenuation coefficient of photosynthetically active radiation (PAR) was 0.13/m, more than three times the average ambient value, and the attenuation coefficient of blue light in the plume (0.105/m) was more than twice the ambient value. Below 25 m, the attenuation coefficients of PAR and blue light in the plume were about the same as in ambient water, and the 1% light depth was 20 m shallower in the plume (70 m) than in ambient water (Ozturgut et al. 1980; Ozturgut, Lavelle, and Burns 1981).

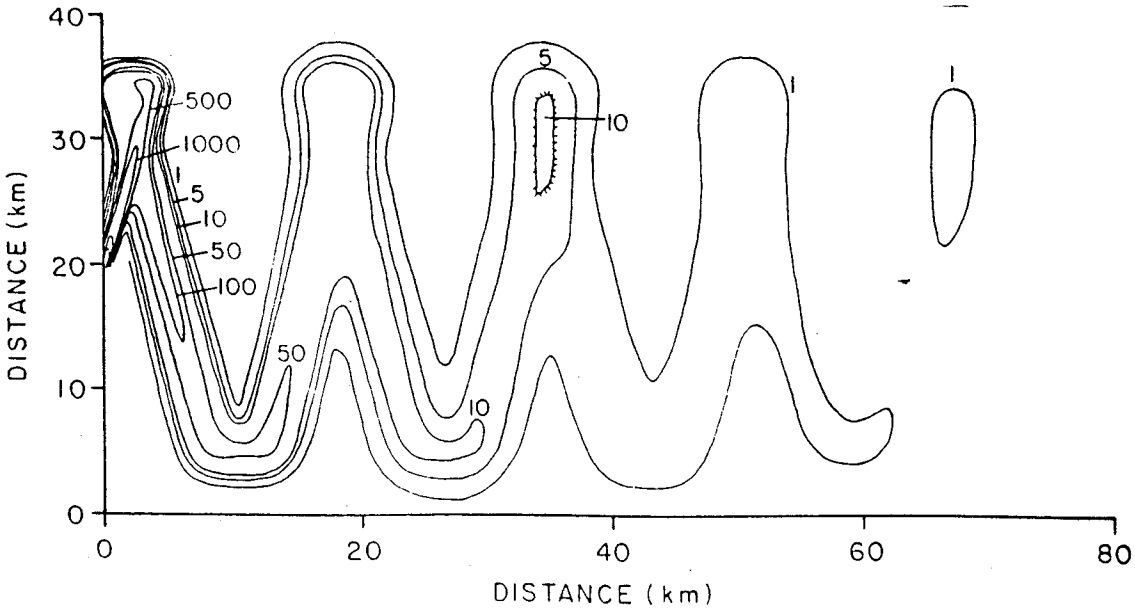

Figure 15.--Calculated surface plume of a commercial mining ship traversing a rectangular pattern oriented normal to the advection direction at advection velocity of 25 cm/s and mining ship speed of 1 m/s. Concentrations of particulates in suspension are given in μg/ℓ (Lavelle and Ozturgut 1981).

During test mining, cold bottom water of 4° to 10°C (mean = 7°C) was discharged over the ship's side through a 30-cm pipe. The water was allowed to fall onto the sea surface 3 m below the pipe at a rate of 120 ℓ/s (Ozturgut, Lavelle, and Erickson 1981). The discharge water mixed rapidly with the surface water and was undetectable in CTD casts after 1 h (E. Ozturgut, Ozturgut Oceanographics, Inc., Seattle, Washington, pers. commun., October 12, 1982). Under commercial mining operations, the volume of discharge would be three times that of the test miner, but since the mining ship's speed would be four times greater, the discharge volume per unit ocean area would be slightly decreased over that of test mining (Lavelle and Ozturgut 1981). Thus, the dissipation of cold water would not be much different from test mining.

Trace metals could be introduced into the water column from bottom water or released from sediments and nodule fragments in the discharge. Since dissolved trace-metal content of bottom and surface layers are not too different, there should be no detectable trace-metal increases at the surface due to the discharge of bottom water. Deep-sea clays, however, are particularly enriched in many heavy metals, and along with nodule fragments, could release trace metals directly to the water column and be taken up by plankton (Ozturgut, Lavelle, and Burns 1981).

Based on estimates of commercial mining discharge rates of selected particulate trace metals, Hanson et al.[1] showed that Al and Fe principally

[1]Hanson, P. J., A. J. Chester, and F. A. Cross. 1982. Potential assimilation by and effects on oceanic zooplankton of trace metals from manganese nodule fragments discharged from planned ocean mining operations. Southeast Fisheries Center, National Marine Fisheries Service, NOAA, Beaufort. NC 28516. Manuscript prepared for NOAA, Division of Ocean Minerals and Energy, Rockville, MD 20852.

from sediments and Mn from nodule fragments were the most abundant (discharge rates of 1,100-1,700 g/s); followed by Ba, Ni, Cu, and Co (12-77 g/s); and Zn, Pb, Mo, V, and Cr (1.4-9.5 g/s). By integrating the discharge rates over the mining year and by comparing them with the annual atmospheric deposition rates, which were the principal steady state inputs of trace metals to the mixed layer, the authors demonstrated that the discharge rates exceeded the deposition rates by several orders of magnitude and concluded that the mining discharge could significantly increase the levels of some metals and alter the trace metal concentrations.

Experiments with resuspended bottom sediments by Rosenbauer and Bischoff (1978), however, indicated that all concentrations of Ni, Zn, Cr, Fe, Cu, Mn, and Al were below detection limits in oxygenated seawater and only Mn and Ni were released in insignificantly small quantities (0.03 ppm Ni, 0.03-2 ppm Mn) in deoxygenated seawater. Other experiments conducted to assess the amount and direction of metal exchange between artificial seawater and crushed Mn nodules (Benjamin and Felmy 1981) indicated that in the pH range of seawater, the amounts of Co, Cu, and Cd released were below the analytically detectable limit, even in the most concentrated slurry tested (20 g/ℓ).

Impact on Primary Production

Impact of mining on phytoplankton photosynthesis and primary production was examined by Chan and Anderson (1981) in terms of light reduction, nutrient enrichment, and toxic chemical effects. The study indicated that local reduction in primary production due to light attenuation inside the plume was significant; however, because of rapid settling of a large percentage of the sediment particulates, the shading effect on phytoplankton was expected to be only temporary, on the order of several hours. Since the adaptation of phytoplankton to a new light regime takes 1 to 2 days, short-term shading in the discharge plume was not expected to appreciably affect phytoplankton photosynthesis.

Chan and Anderson (1981) assessed the effect of mining on nutrient enrichment from information in the literature. Based on the average discharge rate and the rate of mixing between discharge and ambient water in test mining, the authors calculated that nitrate enrichment would be no more than 0.03 μg-atm/ℓ within the first few minutes and 0.003 μg-atm/ℓ within the first hour. These increases were expected to be below analytical detectability and not to have any appreciable immediate effect on the nitrate-uptake rates and primary production. In the long term the nutrients introduced into the euphotic zone were expected eventually to be incorporated into primary production, but even at full-scale mining rates the increase in primary production due to one or even a dozen mining vessels was not expected to create any significant change in the marine food chain.

Experiments conducted by Chan and Anderson (1981) to study the effects of heavy metals and other toxic substances indicated that the mining discharge had no effect on the short-term photosynthetic rate, even when these substances were present at a fairly high concentration. Due to the insignificant amount of heavy metals from bottom sediment and the rapid mixing and dispersal of the mining discharge, any long-term toxic effect was considered negligible.

Impact on Microzooplankton

The effects of mining discharge on microzooplankton have not been investigated. Any effect on these organisms could be catastrophic since they are essential for first-feeding fish larvae. Although fish larvae are dependent on these food items for a brief period only, they represent an essential first step in ensuring the survival of the larvae.

The potential effects of mining on macrozooplankton have been examined by Hirota (1981) from limited field data (three replicate neuston net tows each in ambient water and discharge plume at two test mining sites) and in laboratory experiments. The standing stocks of macrozooplankton, based on neuston net tows, were significantly higher in ambient water at one mining site and in plume water at the other. The similarity of occurrences of macrozooplankton taxa in ambient and plume localities were equally high at both mining sites. Stock abundance and taxonomic composition at the surface were apparently unaffected by the mining plume, at least over a short-term period.

Laboratory experiments with 12 species of copepods exposed to low-to-medium particulate concentrations, including the range of concentrations observed during test mining, have been made to determine mortality rates (Hirota 1981). The difference in mortality between treatments and controls was <5% for most species after 24 h and only slightly higher (within 10%) after 48 h. The results indicated that mining discharge at the concentrations used in the experiments and observed in test mining plumes did not cause unusually high mortality.

The study by Hirota (1981) also included the examination of fecal pellets from copepods and measurements of rates of fecal pellet production, pellet size, and sinking speeds. On the basis of this study as well as studies by other workers, Hanson et al. (see footnote 1) suggested that zooplankton will ingest significant quantities of particulate matter injected into surface waters, which could lead to assimilation of trace metals. From results of feeding experiments in the literature, they concluded that assimilation of trace metals from food through the gut walls of zooplankton was not particularly efficient and that normal processes of elimination, such as excretion (both soluble release and fecal pellet production), molting, and egg laying, appeared to rapidly reduce the levels of trace metals that were initially incorporated into tissue.

Impact on Fish

Adults

There have been relatively few studies on the effects of suspended particulates and turbidity on pelagic marine fishes. Most of the studies have focused on the physiological and pathological effects of high turbidity on freshwater and estuarine species. Many of these fishes that are normally exposed to high turbidities in nature are not bothered by high test turbidities (Wallen 1951; Herbert and Merkens 1961; Alabaster 1972, 1977; Sherk 1972; Neumann et al. 1975). Wallen (1951) and Alabaster (1972, 1977) reported that particulate concentrations below 60 mg/ℓ were not harmful to trout, *Salmo gairdneri* and *S. trutta*; however, physiological effects have been observed in some fishes at much higher turbidities. Prolonged exposure to excessively high turbidities have produced clogged gill cavities

resulting in suffocation (Everhart and Duchrow 1970, cited by Swenson and Matson 1976) and abnormal changes in the gills (Herbert and Merkens 1961; Alabaster 1972). Alabaster (1972) found thickening and fusion of the epithelial cells of the secondary lamellae in some S. trutta taken from rivers carrying particulate concentrations of 1,000 and 5,000 mg/ℓ. Herbert and Merkens (1961) observed that survival of rainbow trout, S. gairdneri, was adversely affected in laboratory tests at concentrations of 270-810 mg/ℓ.

The turbidity caused by suspended particulates affect fish in other ways, most importantly in their feeding behavior, by making it more difficult for the fish to see their prey. Vinyard and O'Brien (1976) observed that at constant light intensity the reactive distances of bluegills, Lepomis macrochirus, to Daphnia diminished as turbidity approached 30 Jackson Turbidity Units (JTU) (ca. 44 mg/ℓ). Gardner (1981) noted a significant reduction in the feeding rates of these fish as turbidity was increased from 60 to 120 and 190 Nephelometric Turbidity Units (NTU) (ca. 88, 177, and 280 μg/ℓ, respectively). Reduction in feeding rate due to turbidity could ultimately lead to a reduction in growth (Sykora et al. 1972). Heimstra et al. (1969) found a general decrease in activity of juvenile largemouth bass, Micropterus salmoides, exposed to turbidities of 14-16 JTU (ca. 21-24 μg/ℓ) and Shiraishi and Shimada (1972) reported that activity of downstream migrating salmonid fish was reduced by increased turbidity.

Information on purely marine species is limited. Ritchie (1970) detected no ill effects of overboard dredge disposal on 44 species of fish in upper Chesapeake Bay. Pruter and Alverson (1972) indicated that abundant flora and fauna, including albacore and salmonids, flourish offshore from the mouth of the Columbia River in water containing particulate concentrations of 10-100 mg/ℓ. Moore and Moore (1976) showed that turbidity reduced the ability of European flounder, Platichthys flesus, to see epibenthic prey and increased the time required to capture pursued prey. Wilson and Connor (1976) found that whitebait (immature clupeoids) avoided the edge of advancing "white water" mass polluted with china clay, whereas mackerel, Scomber scombrus, did not. It seemed that small numbers of mackerel entered the polluted water and, although being visual feeders, were able to locate prey (fishing lure).

The only study of turbidity and tuna was done by Barry (1978), who observed the reaction of captive yellowfin tuna and kawakawa to a turbidity cloud of suspended particulates of deep-sea mud from the DOMES area. No ill effects were observed as a result of short exposure to turbidities ranging from 6 to 40 NTU (ca. 9-59 mg/ℓ). Behavioral responses were mixed. Although tunas were sometimes observed to avoid the turbid cloud, they readily passed through it, as the cloud circled the tank. Maximum turbidities at the point where tunas passed through the cloud ranged from 1.6 to 3.0 NTU (2.7-4.7 mg/ℓ) for yellowfin tuna and 1.7 to 4.43 NTU (2.28-6.8 mg/ℓ) for kawakawa, and feeding occurred in turbidities to 7.4 NTU (11.2 mg/ℓ). The preliminary experiments by Barry indicated also that in DOMES mud turbidities greater than 2.5 NTU (4 mg/ℓ), the test tunas sometimes became sufficiently upset to stop feeding and exhibited coughing behavior. Barry pointed out that it would be difficult to extend these findings to tunas in the wild, since (1) the captive tunas may have developed a higher tolerance to turbidity because of their exposure to algae-produced turbidity in the tank, and (2) the ability of tunas to detect turbidity clouds in the wild might be different from that of captive tunas.

Reduction in the feeding rate of adult tunas in the mining plume need not be a large concern, however, because of the low concentration of particulates, the transitory nature of the plume, the ability of tunas to feed in turbid waters, and most importantly, the capability of the tunas to swim through and out of plume waters. The only possible effect to tunas could be the reduction of food organisms in plume waters as a result of a reduction in primary productivity. Food organisms (Hirota 1981) and primary production (Chan and Anderson 1981), however, have been shown to be little affected by the discharge plume. No studies have been done on the behavior of adult billfishes to turbid waters. Based on the similarity of their feeding habits (types of food eaten) with that of adult tunas and on their great mobility, they too should be unaffected by the discharge plume.

Tuna and Billfish Larvae

There have been some studies on the effects of suspended solids and turbidity on fish larvae, but hardly any on larvae of tunas and billfishes. The effects of plume water on larvae of tunas and billfishes must, therefore, be inferred from studies made of other fish larvae. The normal development of embryos, larvae, and postlarvae of fishes in the mining area could be affected by sedimentation, loss of illumination due to turbidity, and changes in the properties of water, such as temperature.

Sedimentation.--There have been only limited studies on the direct effects of sediment on the early developmental stages of fishes. Rosenthal (1971) observed that there were major decreases in egg hatching success and survival of herring larvae, *Clupea harengus*, at high concentrations of "red mud" (600-7,000 mg/ℓ), and that the development of the embryos were retarded. He reported also that the number of embryonic malformations increased with increasing concentrations, due to the adherence of mud particles to the eggshells and thereby possibly interfering with gaseous and other exchanges between the eggs and surrounding medium. He further noted that the ingestion of red mud particles by the larvae eventually resulted in blocked food intake. Sherk et al. (1975) noted that exposure of estuarine fishes to sublethal concentrations of suspended solids significantly increased hematocrit value, hemoglobin concentration, and erythrocite number, indicating respiratory stress, and that the early life stages of these fishes were more sensitive to suspended solids than the adults. They reported also that 18-h exposure to fuller's earth in concentrations of 0.8 g/ℓ resulted in 100% mortality of juvenile bluefish, Pomatomidae. Swenson and Matson (1976) reported that growth and survival of lake herring, *Coregonus artedi*, larvae held for up to 62 days in experimental tanks were not affected by red clay concentrations ranging from 0 to 48 Formazon Turbidity Units ca. 1-28 mg/ℓ). No differences were found in mortality nor average weekly growth rates over the observed range of red clay concentrations.

Direct effects of sediment on estuarine and freshwater fishes, such as those mentioned above, generally occurred after prolonged exposure to high sediment concentrations ranging from 270 to 7,000 mg/ℓ. While these fishes have greater tolerance than ocean species to suspended particulates, the lower levels of concentrations and the rapid dissipation of sediments at the mining sites should lessen the impact on eggs and larvae of the latter species. In the test mining area, the maximum concentration of particulates 15 min after initial mixing was (ca. 900 μg/ℓ) Ozturgut, Lavelle, and Burns 1981) and the concentration of particulates was found to dissipate rapidly

to near ambient in <5 h (Burns et al. 1980). The rapid dissipation of sediment concentration and the rapid development of tuna embryos (hatching occurs in about 1 day after fertilization) would allow the eggs minimal exposure time to sedimentation and thus reduce or negate embryonic malformation. As for the newly hatched larvae, feeding generally begins in 2 to 3 days after hatching. By this time, of course, the concentration of sediment particulates should be at or near ambient and thus not pose any danger to the larvae in causing blocked food intake or in affecting their growth. The only likely effect of sediment would be to those larvae already in the feeding stages. However, in view of the rapid dissipation of the discharge, the exposure time would be confined to a matter of hours and, therefore, should not noticeably affect the growth of the larvae. Under commercial mining conditions, where discharge volumes per unit ocean area are expected to be slightly less than that of mining tests (Lavelle and Ozturgut 1981), the chances of sediment particulates directly affecting tuna eggs and larvae should be negligible.

Turbidity.--Feeding is the prime activity of all fish larvae for survival. The success or failure in feeding will depend not only upon the searching power and reactive distance of the larvae, their feeding efficiency, and the abundance of suitable food organisms present (Blaxter 1965), but also on illumination. Blaxter (1980), in his review of vision and feeding of fishes, reported that the ability of fish to feed fell progressively during dusk or as the illumination was artificially reduced. The threshold illumination for feeding by more than 20 species of fish averaged about 0.1 lux. He reported also that the ability to perceive prey and to feed successfully fell progressively for larvae of some species (herring, plaice, and northern pike, *Esox lucius*) during dusk or as illumination was reduced. Kawamura and Hara (1980) noted that milkfish, *Chanos chanos*, larvae also could not take food in the dark, but that the juveniles were able to do so. For these larvae, feeding thus would be limited to daylight hours, and any reduction in illumination due to turbidity will in effect decrease the hours available for feeding or limit feeding activity to less than optimum levels.

To compensate for reduced illumination, the larvae will be required to depend even more greatly upon their swimming power to ensure sufficient prey contacts and upon their reactive distance and feeding efficiency. Bishai (1960) found that herring larvae 6-8 mm long could sustain a water current of 0.57-1.03 cm/s for at least 1 h, giving them the possibility of swimming 20-30 m in 1 h. Presumably larger and stronger larvae will have greater swimming capabilities and enable them to cover greater distances within daylight hours. For larvae smaller than 6 mm, however, distance covered and reactive distance, as well as feeding efficiency, would be greatly reduced in most species. In most fish larvae, the distance at which they react to prey is quite short. Herring larvae were found to react to prey at distances of 0.7-10 body lengths when they first started feeding (Rosenthal and Hempel 1970). Blaxter and Staines (1971) reported reactive distances of 0.4 body length for herring, 0.5 body length for plaice, *Pleuronectes platessa*, and sole, *Solea solea*, and 0.2 body length for pilchard, *Sardina pilchardus*. Hunter (1972) found the reactive distance of northern anchovy, *Engraulis mordax*, to be 0.4 body length. The larvae of all species, except plaice, were reported as having low feeding success (2-10%) at initial feeding. Plaice had high success rates (32-62%) due to their increased maneuverability and ability to swim backward. The short reactive distance and low feeding efficiency at first feeding would

be lessened even more by reduced illumination, which in effect would reduce the availability of food. Thus, growth and survival would be affected, as it has been observed in feeding studies of larvae of plaice (Riley 1966; Wyatt 1972), sea bream, Archosargus rhomboidalis (Houde 1975), bay anchovy, Anchoa mitchilli (Saksena and Houde 1972; Houde 1977), sardine, Harengula pensacolae (Saksena and Houde 1972), and lined sole, Achirus lineatus (Houde 1977). To compensate for reduced reactive distance resulting from lower illumination, it will be necessary for the larvae to increase prey contacts. Hunter and Thomas (1974) observed such an adjustment in larvae of anchovy, which increased their swimming speed and area of search at low prey densities.

Although light intensity is important for the survival of larvae, light intensity alone may not directly influence embryonic development. Ciechomski (1967a) observed that eggs of anchovy, E. anchoita, kept in complete darkness developed and hatched in a normal way. In other tank experiments, Houde and Palko (1970) noted that mortality of sardine larvae was higher in a tank with poor lighting (one 75-W incandescent bulb) than in one with better lighting (two 40-W fluorescent bulbs). Riley and Thacker (1963) also reported high mortalities for larvae of plaice reared under poor light conditions (total light at the surface was below 30-ft candles).

Undoubtedly, the feeding of tuna and billfish larvae will be affected by reduced illumination. They should be able to compensate for this, however, by their greater swimming power, feeding efficiency, and better vision because of their larger eyes and mouth, and earlier development of fins than most other fish larvae. The rapid growth exhibited by these larvae should further aid them to survive and pass through the critical early life stages.

Turbidity also affects larvae in other ways. Swenson and Matson (1976) noted that herring larvae had a tendency to concentrate closer to the surface when subjected to high turbidity. They attributed this reaction to reduced light levels at the bottom of the turbid water chambers and suggested that such a reaction in the wild could indirectly influence survival by exposing the larvae to greater predation. Miller (1974), in his survey of larval fish in waters off sugar mills, sewer outfalls, oil refineries, thermal outfalls, urbanized areas with associated runoffs, and in harbors in the Hawaiian Islands, noted that species of fish larvae, including tunas, in turbid water were lower in density by 75% and in number by 55%, and that turbidity, whether natural or artificial, was negatively correlated with larval fish abundance. This study implies that fish larvae in the wild avoided turbid waters. If this is so, it does not seem likely that mortality by predation would be significantly increased in plume waters, as suggested by Swenson and Matson (1976).

Environmental factors.--Salinity, oxygen, and temperature also affect the early development of fishes, particularly in the embryonic and larval stages. Ciechomski (1967a) noted that the embryonic development of anchovy occurred normally at salinities of 25.8-50°/oo, but salinities above or below this range produced pronounced abnormalities in the embryos. Fonds et al. (1974) found that survival of garfish, Belone belone, eggs was influenced predominantly by temperature, but the survival of larvae from hatching to 30-40 mm TL was influenced by both salinity and temperature. Survival of eggs and larvae was found to be maximized at salinities of

31.4-37.1°/oo and temperatures of 17.4°-19.4°C, and the limits for survival of eggs were estimated at salinities of <10 to >45°/oo, and temperatures of 12°-24°C. In other experiments, garfish eggs failed to develop at a salinity of 5°/oo. In laboratory experiments on the effects of dissolved oxygen on striped bass, Morone saxatilis, eggs and larvae, Turner and Farley (1971) observed that reductions in dissolved oxygen from saturation (7.3-8.8 mg/ℓ) to 4 and 5 mg/ℓ adversely affected hatching success and survival of the larvae. Egg survival was found to decrease with an increase in temperature (from 18.3° to 22.2°C) or exposure time (from 6 to 56 h), or a decrease in oxygen level. At an oxygen level of 4 mg/ℓ, survival was consistently reduced for all exposure times, the length of time for hatching was longer, and a number of larvae hatched with various abnormalities.

Based on these studies, it seems that detrimental effects occur at either extremely high or low salinity levels--normal development takes place over a fairly wide salinity range--and after some hours of exposure to reduced dissolved oxygen levels. Although the levels at which these effects occur in eggs and larvae of billfishes and tunas could differ from the species noted above, the overall effects may be similar. In the mining area, however, ill effects from salinity and dissolved oxygen in the discharge water should be minimal because of the absence of extreme concentrations, such as those used in experimental tests, and because of the rapid mixing of the discharge water. During test mining, the salinity of the water at depths greater than 5,000 m was 34.72 ±0.01°/oo (Burns et al. 1980), which was well within the seasonal range of 33-35°/oo in the surface mixed layer (Ozturgut et al. 1978). From monitoring tests (Ozretich 1981), the mean oxygen concentration in 1-, 2-, and 3-h-old plume was reported as 4.688±0.035 ml/ℓ, nearly the same as the ambient mean concentration of 4.695±0.05 ml/ℓ, and the maximum dilution of the discharge water was reported to occur within the first few minutes of mixing with surface water.

Temperature appears to have a predominant influence in the development of embryos and larvae. Most fish eggs and larvae were found to survive a wide range of temperatures: 14°-22°C by striped bass (Morgan et al. 1981), 10°-17°C by anchovy (Ciechomski 1967a), 11°-20°C by tiulka, Clupeonella delicatula delicatula (Pinus 1974), and 23°-30°C by yellowfin tuna (Harada et al. 1978), to mention a few. At temperatures below or above the normal ranges, however, the development of embryos and larvae could be affected drastically. Ciechomski (1967a) observed that a temperature of 4°C water in the early blastula stage showed a complete halt in their development, death occurred in 5 to 6 days, and eggs which had been kept for 1 to 2 days at 4°C and transferred to normal temperature (14°C) died more quickly, suggesting that lower temperature may cause irreversible damages. At low temperatures (10°-12°C), larvae of striped bass were found to hatch with a depressed cephalic region (Morgan et al. 1981) and the larvae of yellowfin tuna were found to be deformed when hatched in temperatures below 20°C (Harada et al. 1978). Larvae of Pacific cod became so inactive at very low temperatures that they were unable to catch and consume food (Alderdice and Forrester 1971). At temperatures higher than the normal range, hatched larvae of striped bass showed pugheaded features, small yolk sacs, and deformed internal organs (Morgan et al. 1981), and larvae of anchovy exhibited an increase in heartbeat from 65-70 beats/min to about 100 (Ciechomski 1967a).

Fish larvae can be affected also by thermal shock when subjected to sudden changes in temperature. Hoss et al. (1974) noted that larvae of Atlantic menhaden, Brevoortia tyrannus; spot, Leiostomus xanthurus; pinfish, Lagodon rhomboides; and three species of flounders, Paralichthys dentatus, P. lethostigma, and P. albigutta, acclimatized at 5°, 10°, and 15°C and subjected to 15°-18°C increases in temperature showed immediate reactions, such as loss of equilibrium, erratic swimming, violent jumping, and convulsions. This initial period of reaction was often followed by a return to relatively normal behavior. These fish also received a thermal shock when they were returned to the original temperature. This second shock was often more violent than the first and was more pronounced at the lower acclimatization temperatures. According to the authors, the second shock may be a direct cause of mortality, or if the fish are not killed, they may be more vulnerable to predation. Griffith (1978) noted that threadfin shad, Dorosoma petenense, acclimatized at 15°C and exposed to sudden cooling (2°-5°C decreases in 4 h) lost equilibrium in proportion to the magnitude of temperature decrease, as the temperature approached 4°-6°C, and that as much as 32% of the cold-shocked fish that had lost equilibrium for as short a time as 12 s before being returned to warmer water could not recover and experienced mortality.

Eggs and larvae of tunas also could be affected by temperature as noted above. Because of rapid dissipation of the cold discharge water soon after initial mixing, such effects would be limited to the area immediately beneath the outfall. With the ambient surface temperature ranging from 21° to 26°C in the mining area and that of the discharge ranging from 4° to 10°C, the difference in the temperatures (17°C) would be similar in magnitude to that tested by Hoss et al. (1974) for other fish species. With thermal shock likely to produce an immediate reaction, there is reason to believe that eggs and larvae coming into direct contact with the cold discharge water would be affected adversely.

Assuming that all tuna eggs and larvae coming into direct contact with the cold discharge water were to suffer mortality, a rough estimate of the total number of larvae that could be killed can be made and the losses evaluated in terms of the magnitude of the annual catches (see section on Effects on Fisheries).

Under full-scale mining operation, bottom water will be discharged at the surface through a 30-cm pipe. The discharged water will fall to the surface from a height of approximately 5 m and impact a swath of surface water approximately 1-m wide, 1-m deep, and 89.4-km long (mining ship speed of 1 m/s) per day. Thus, the volume of water affected per day would be 86,400 m^3. Based on surface day and night plankton net catch data from within the planned mining area (Matsumoto 1958; Strasburg 1960; and unpublished data, Honolulu Laboratory files), the concentrations of tuna larvae were approximately 0.89 skipjack and 0.30 yellowfin tunas per 1,000 m^3. Hence, 77 skipjack tuna and 26 yellowfin tuna larvae (larval concentration times 86,400/1,000), could be affected by the discharge water each day. These numbers, however, represent only larvae past the initial feeding stage and do not include eggs and yolk sac larvae which, although present, were not analyzed in the larval studies. Size-frequency data from Strasburg (1960) indicate that about 33% of the skipjack tuna larvae and 29% of the yellowfin tuna larvae taken in plankton net tows were at the initial feeding stage (3.0-3.9 mm TL). Assuming that eggs and 1- and 2-day-old yolk sac larvae were present at the time net tows were made and

each stage survived to the first feeding stage in 1 to 3 days—in like numbers, then an additional 76 skipjack tuna (77 × 0.33 × 3) and 23 yellowfin tuna (26 × 0.29 × 3) larvae would be affected, bringing the total eggs and larvae affected per day to 153 skipjack tuna and 49 yellowfin tuna. In 300 mining days, the effort required to achieve the estimated annual production of 1.5 million tons of ore (Ozturgut, Lavelle and Erickson 1981), ca. 45,900 skipjack tuna larvae and 14,700 yellowfin tuna larvae could be susceptible to thermal shock each year.

These estimates represent the maximum number of larvae that could be affected if mining were done entirely in areas where spawning by both species occur. Skipjack tuna, however, do not spawn in the northeastern quarter (north of lat. 10°N and east of long. 140°W) of the projected mining area. Consequently, the number of skipjack tuna larvae likely to be affected by mining will be reduced in proportion to the time (days) mining is done in this sector.

Other Possible Effects

Tunas, as well as other pelagic fishes, have been known to congregate under drifting objects, such as logs, seaweed, rafts, and other flotsam. Fishermen have utilized this behavior of fishes by seeking and fishing around such objects, often with huge success (Uda 1933; Kimura 1954; McNeeley 1961; Inoue et al. 1963, 1968). In recent years manmade fish aggregating devices (FAD's) have been devised and anchored in coastal and deep open ocean waters in the Philippines (Murdy 1980; Aprieto 1981, de Jesus 1982, Matsumoto[2]), Hawaii (Matsumoto et al. 1981), many central and South Pacific Islands, New Zealand, Australia, and in the Indian Ocean (Shomura and Matsumoto 1982), and in the eastern Pacific (Guillen and Bratten[3]) (Fig. 16). These FAD's have attracted fish, predominantly tunas, in sufficiently large concentrations to entice commercial tuna purse seiners and pole-and-line vessels to fish around them. In Hawaii, pole-and-line fishing vessels caught over 471 MT (1 million lb) of skipjack tuna and 45.4 MT (100,000 lb) of yellowfin tuna off four FAD's in 1978 (Table 1). In the Philippines estimates of up to 200 MT of various species of tunas, including skipjack, yellowfin, bigeye, kawakawa, frigate, and bullet, have been taken in a single purse seine set (see footnote 2).

Tunas of varied sizes ranging from <1 to >45 kg have been reported from beneath and around FAD's (Matsumoto et al. 1981). Small tunas (<1 or 2 kg) generally remained close to the FAD's during the day and night, but larger tunas (>3 kg), particularly the skipjack tuna, roamed over distances of 5 km or more away from the FAD's during daylight. The latter departed from the FAD's at sunrise and returned to it at sunset. The ability of the skipjack tuna to depart and return to a reference point has been demonstrated by Yuen (1970). By tracking bank-associated small (40-44 cm)

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[2]Matsumoto, W. M. Manuscr. in prep. Payao fishing in the Philippines. Southwest Fisheries Center, National Marine Fisheries Service, NOAA, P. O. Box 3830, Honolulu, HI 96812.

[3]Guillen, R., and D. A. Bratten. 1981. Anchored raft experiment to aggregate tunas in the eastern Pacific Ocean. Inter-Am. Trop. Tuna Comm., Internal Rep. 14, 10 p. Inter-American Tropical Tuna Commission, c/o Scripps Institution of Oceanography, P. O. Box 1529, La Jolla, CA 92093.

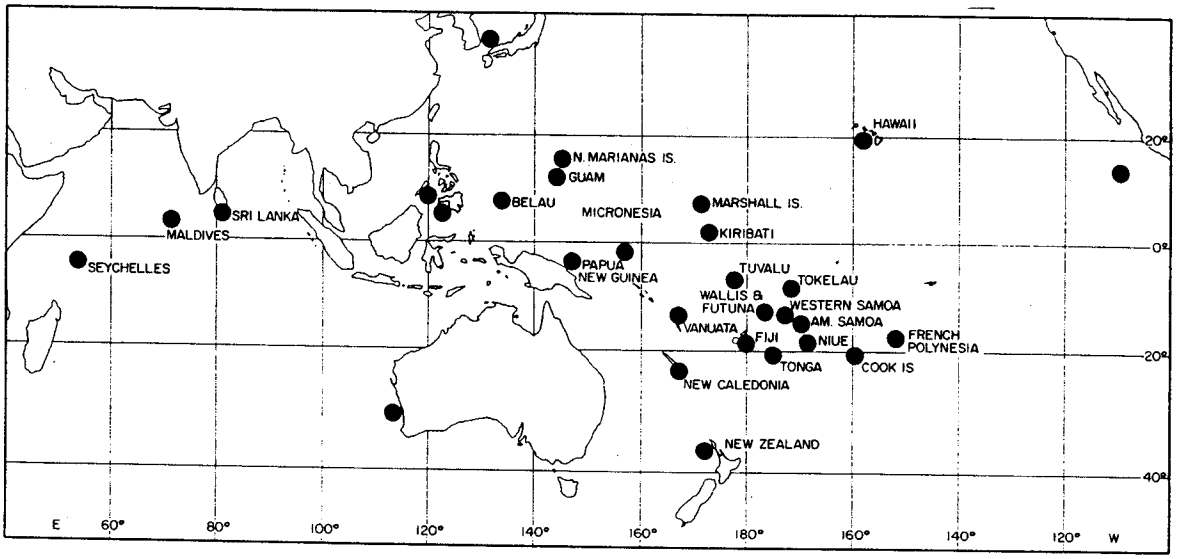

Figure 16.--Locations where fish aggregating devices have been deployed, 1979-81, or where deployment is planned in the Pacific and Indian Oceans (Shomura and Matsumoto 1982).

Table 1.--Fish species caught (in pounds) by pole-and-line fishing in 1978 during the Hawaiian fish aggregating device experiment (Matsumoto et al. 1981).

		Skipjack tuna		Yellowfin tuna		Kawakawa		Dolphin		Total	
Buoy	Visits	Catch	Catch per visit	Catch	Catch per visit	Catch	Catch per visit	Catch	Catch per visit	Catch	Catch per visit
A	92	357,044	3,880.3	22,682	246.5	1,479	16.0	854	9.3	382,031	4,152.5
B	1	5,110	5,110.0	0	0.0	0	0.0	0	0.0	5,110	5,110.0
C	14	103,037	7,359.8	1,475	105.4	4,218	301.3	0	0.0	108,730	7,766.4
D	139	573,106	4,123.1	80,183	576.9	1,706	12.3	3,034	22.6	658,029	4,734.0
Total	246	1,038,297	4,220.7	104,340	424.1	7,403	30.0	3,888	15.8	1,153,900	4,690.6
Percent of total catch		89.73		9.28		0.64		0.34		99.99	

skipjack tuna tagged with an ultrasonic device, Yuen showed that the fish was capable of making nightly journeys of 25-106 km (maximum straight line distances of up to 35 km from the bank). The tagged fish was observed to leave the bank at nightfall, returning to it at sunrise, and remaining over the bank throughout the day as a member of a school. This pattern of daily movement was observed for 3 days and again for 3 more days after an interruption of 2 days, when the vessel was required to return to port. The repeated daily pattern from and return to the bank led Yuen to conclude that the skipjack tuna was able to navigate and was aware of time.

The ability of the skipjack tuna to depart and return to a FAD can significantly alter the normal distributional pattern of schools within an area. After having made initial contact with a FAD, a school may prolong its stay in the area. In due time this would result in a buildup of schools around the FAD, as observed by Matsumoto et al. (1981). During the

peak fishing season, the FAD's attracted more tuna schools than normally would have been found in the area. The schools attracted to the FAD's remained in the vicinity or were replaced by other schools on a continuing basis, allowing the pole-and-line fishing vessels to fish around the FAD's for periods of up to 18 consecutive days.

In the Hawaiian FAD's study, Matsumoto et al. (1981) reported that two or more schools were present around a FAD at the same time during April and May. The long-term (1950-61) sightings of skipjack tuna schools in Hawaiian waters for a comparable period (March-May) is given as 0.87 schools per 10 h of scouting (Waldron 1964). Based on these sightings, FAD's could increase the number of schools within its vicinity by a factor of three or four. In nodule mining, the ship, moving slowly at a speed of 1 m/s, could act as a FAD and accumulate tuna schools. Should spawning occur at this time, the concentration of spawned eggs around and in the path of the mining ship would be higher than usual, and the number of eggs that would eventually be exposed to direct contact with the cold discharge water also would be increased. A threefold or fourfold increase, as noted above, may not be unreasonable.

Effects on Fisheries

Mortality of tuna eggs and larvae caused by mining is bound to have some effect on the catches in the eastern Pacific surface fishery and the Hawaiian skipjack tuna fishery. The eastern Pacific fishery is a major fishery: The catch of skipjack tuna reached a high of 170,000 MT in 1978 and averaged 128,300 MT annually in the 5-year period prior to 1980 (Forsbergh 1980). The catch of yellowfin tuna reached a high of 236,400 MT in 1976 and averaged 201,000 MT annually over the same period (Cole 1980). The Hawaiian skipjack tuna fishery is a minor fishery, with annual catches for the same period averaging 3,100 MT (unpublished data, Honolulu Laboratory files).

A crude estimate of the probable impact mining will have on the recruitment of 1-year-old fish can be made from available length-frequency and catch data. The eastern Pacific fishery can be separated at lat. 15°-16°N off the coast of Mexico into a northern and southern fishery. Nearly all of the fish entering the northern fishery originate in equatorial waters from an area west of long. 130°W, within and north of the NECC (Rothschild 1965; Fink and Bayliff 1970; Williams 1972). In the period 1971-74, the mean annual catch in the northern fishery was 9,747 MT of skipjack tuna and 24,833 MT of yellowfin tuna (Calkins 1975). Based on earlier published data (Davidoff 1963; Broadhead and Barrett 1964), 1-year-old (below 50 cm) skipjack tuna averaged 24.0% by weight of the catch in the northern fishery and 1-year-old (below 60 cm) yellowfin tuna averaged 0.9% of the yellowfin tuna catch. Assuming that the proportion of 1-year-old fish remained the same in the 1971-74 period, the average annual catch of this age group would represent approximately 2,336 MT for skipjack tuna and 2,235 MT for yellowfin tuna.

From earlier estimates, roughly 49,500 skipjack tuna and 14,700 yellowfin tuna larvae were expected to be affected by mining each year. In a nonmining situation, these larvae would be expected to suffer a natural mortality of 80% (Murphy and Sakagawa 1977) during the year. Adjusting for natural mortality, 9,900 skipjack tuna and 2,940 yellowfin tuna larvae should survive and enter the fishery as 1-year-old fish. These numbers

represent approximately 15.3 MT of skipjack tuna and 10.7 MT of yellowfin tuna, based on an average weight of 1.85 kg for 40-50 cm skipjack tuna and 3.17 kg for 50-60 cm yellowfin tuna (length-weight relationship tables, Honolulu Laboratory files). Adjusting for possible FAD-like effects of the mining ship would increase the totals to 65.2 and 42.8 MT for skipjack tuna and yellowfin tuna, respectively. These totals represent only an insignificant amount (0.64 and 0.16%, respectively) of the annual catches of the two species in the eastern Pacific northern fishery. The actual impact on the annual catches would be far less, if the efficiency of the gear, which is well below 100%, were considered.

In the Hawaiian fishery, the skipjack tuna catch consists of fish migrating from the Japanese offshore and the eastern Pacific fisheries, as indicated from recaptures of tagged fish (Matsumoto et al. 1984) and very likely from the central equatorial waters to the south of the islands (Matsumoto 1975). Recruitment of 1-year-olds may be mostly from the mining area to the south. The effect of mining on eggs and larvae could affect the eventual recruitment of 1-year-olds, but unlike the sector east of long. 130°W, where tuna spawning does not occur north of lat. 10°-15°N, heavy spawning by skipjack and yellowfin tunas occur in Hawaiian waters north of the mining area. The larvae spawned could remain in the area and enter the fishery as 1-year-old fish a year later or migrate south into the mining area as juveniles during winter, at sizes large enough to be unaffected by mining discharge waters, and return as 1-year-old recruits. This should lessen the effects of mining insofar as the recruitment of 1-year-olds into the Hawaiian fishery is concerned.

SUMMARY AND CONCLUSIONS

Of the many changes to the environment resulting from nodule mining, increased sediment and turbidity in surface water and the discharge of cold bottom water at the surface were considered most likely to affect tuna and billfish eggs and larvae. The potential effects on the biota were examined in terms of small-scale test mining results and projections to full-scale mining effects were attempted whenever such information was available.

In test mining studies, the maximum concentration of sediment particulates soon after mixing of the discharge and surface waters was given as 900 μg/ℓ (Ozturgut et al. 1980). The surface plume that resulted from mining extended downstream with the concentration of particulates dissipating rapidly to near ambient (55 μg/ℓ) in 5 h at a distance of approximately 5 km from the ship and to ambient (34 μg/ℓ) in about 37 h. Light attenuation in 1-h-old plume at depths of 10-20 m was 0.13/m, more than three times the average ambient value. Cold discharge water, 4°-10°C (mean = 7°C), was found to mix rapidly with surface water and was undetectable in chlorinity-temperature-depth casts after 1 h.

Under commercial mining conditions, with the ship traversing the mining area in a rectangular pattern 30 km on the long side and 3.6 km on the short side, particulate concentration of 100 μg/ℓ was expected at distances of <6 km downstream of the mining ship and concentration of 50 μg/ℓ (near ambient) at distances of about 14 km. The latter concentration was expected to be reached in about 15 h. The volume of discharged water was expected to be three times that of the test miner, but because the ship's speed would be four times greater, the discharge volume per unit of ocean was expected to be slightly less than that of test mining (Lavelle

and Ozturgut 1981). Consequently, the dissipation of cold water was expected to be not much different from that of the test mining.

Past studies on the effects of suspended solids and turbidity on fish eggs and larvae have dealt mainly with freshwater and estuarine species. Direct effects of suspended solids on the early developmental stages of fishes included such things as retarded embryonic development, development of malformed larvae, blocked food intake leading to undernourishment and reduced growth, and clogged gills resulting in respiratory stress and mortality. These effects generally occurred at relatively high turbidities of 270 to 7,000 mg/ℓ and after prolonged exposures of 8 or 9 weeks (Rosenthal 1971; Sherk et al. 1975; Swenson and Matson 1976). The combined effects of low concentration and rapid dissipation of particulates in test mining and the extremely rapid development of the eggs and larvae of tunas (embryonic development and hatching of yellowfin tuna in about 1 day in tropical temperatures, yolk absorption in 2-3 days, and growth of larvae from 2.6 mm at hatching to 51 mm in 38 days) were expected to reduce the risk of prolonged exposure and thus prevent any ill effects.

Reduced illumination caused by turbidity has been reported to affect feeding by reducing the reactive distance and feeding efficiency of fish larvae. These effects have been overcome by some species (e.g., herring) which increase their swimming speed and area of search for prey (Hunter and Thomas 1974). Because of the exceptionally large eyes and mouth and the rapid development of the fins in larvae of tunas and billfishes, it was expected that these larvae could compensate for reduced illumination better than most fish larvae. Thus, it was concluded that increased turbidity resulting from mining would not affect the survival of these larvae.

Other properties of seawater, such as salinity, oxygen, and temperature, also were found to affect the development and survival of fish eggs and larvae, but only at extremely low or high levels and after prolonged exposures. Ill effects on tuna eggs and larvae in the mining site should be minimal, however, because of insignificant differences in the salinity of bottom and surface water and the rapid dilution of the low oxygen bottom water after mixing with surface water.

The most likely, and perhaps the only, effect of temperature on the eggs and larvae of tunas will occur at the discharge point of bottom water. In nodule mining, the cold discharge water (4°-10°C, average 7°C) falling onto the sea surface can come into direct contact with the developing eggs and newly hatched larvae drifting at the surface. Such contacts could cause the cessation of embryonic development, the development of deformed larvae, or result in thermal shock to the larvae, causing them to lose equilibrium and become easy targets to predators or even result in death.

Supersaturation of atmospheric gases could be a problem, but in the discharge of an airlift mining operation, supersaturation lasts only minutes due to rapid dilution. Exposure of fish to supersaturated gases, thus, is not expected to be a concern (Ozretich 1981).

Based on the premining concentration of tuna larvae in the surface layer (1 m deep) within the mining area and on the estimated volume of surface water that would be affected by the discharge water in 300 days of mining each year, it was estimated that approximately 45,900 skipjack tuna and 14,700 yellowfin tuna larvae could be lost annually due to mining.

These figures would be about four times larger if the mining ship were to act as a FAD by concentrating tuna schools in the immediate vicinity of the mining ship. Spawning activities by these schools could increase the concentration of eggs near the mining ship. Such increases can easily be threefold or fourfold greater than the concentration in nonmining situations.

The impact of the mortality estimated above on the eastern Pacific northern fishery (north of lat. 15°N) and on the Hawaiian skipjack tuna fishery can be estimated. In the eastern Pacific, practically all of the fish entering the northern fishery originate in equatorial waters west of long. 130°W. Larvae from this region are transported eastward in the NECC and enter the fishery as 1-year-old fish. Fish of this age group comprise 24% by weight (2,336 MT) of the skipjack tuna and 0.9% (2,235 MT) of the yellowfin tuna taken annually in the northern fishery (average annual catches estimated for the period 1971-74). Of the estimated number of larvae that would likely be killed by mining (45,700 skipjack tuna and 14,700 yellowfin tuna), 80% are expected to die of natural causes, leaving 9,900 skipjack tuna and 2,940 yellowfin tuna (equivalent to 15.3 and 10.7 MT, respectively) to survive and enter the fishery as 1-year-old fish. Adjusting for possible FAD-like effects of the mining ship would increase the totals to 65.2 and 42.8 MT for skipjack and yellowfin tunas, respectively. These totals, representing approximately 0.64 and 0.16% of the annual catches of skipjack and yellowfin tunas, respectively, should have no noticeable effect on the total annual catches of both species taken in the eastern Pacific northern fishery.

In the Hawaiian fishery, the impact of mining on the skipjack tuna fishery would be even less, since the species also spawns in the fishing grounds, outside of the projected mining area (i.e., north of lat. 20°N). Larvae from these spawnings could remain in the area and be subjected to fishing a year later (as 1-year-olds) or migrate south into the mining area in winter as juveniles, at sizes large enough to withstand the impact of mining, and return as 1-year-old fish in the summer, together with fish spawned within the mining area.

Based on this study, the probable effects of mining on tuna and billfish eggs and larvae appear to be negligible; however, the premises on which certain deductions have been made, require verification. Laboratory studies to accurately describe the effects of sediment and temperature on tuna eggs and larvae and on the spawning behavior of adult tunas need to be made. In the field, more detailed observations on the temperature of the water at the point of discharge are needed and the effect of the discharge water on tuna eggs and larvae at the point of mixing need to be determined. The abundance of tuna and billfish eggs and larvae along the path of the mining ship needs to be determined routinely, so that the extent of the damage to these life stages can be monitored. If damage to the eggs and larvae by the discharge is found to be excessive, then alteration of the discharge point, perhaps to subsurface levels, may be necessary.

Aside from these studies concerning direct effects on eggs and larvae, additional studies are needed on the pelagic food web. It is recommended that the effects of sediment and temperature on all components in the food web be studied, particularly those organisms which are consumed during initial feeding by the larvae.

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