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Drift-tube study of the dispersal potential of green abalone *(Haliotis fulgens)* larvae in the southern California Bight: implications for recovery of depleted populations

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ABSTRACT: Drift tubes were released over the major past and present green abalone *(Haliotis fulgens)* beds in southern California, USA, to investigate the dispersal potential of this species' relatively short-lived larvae. The Channel Islands presently support the important green abalone populations in this region; mainland stocks are largely depleted. A total of 2400 drift tubes was released during June and October 1981, the 2 peaks of the spawning season. Of the 1225 drift tubes released at the Channel Islands, 4 % were later recovered in the mainland, but only 0.4 % were found within a time span appropriate for green abalone larval life. There was some transport between isolated mainland populations within appropriate time periods but the present status of mainland stocks suggests that recolonization by larvae originating elsewhere will be uncommon. In contrast, high proportions of the drift tubes deployed in each general release area were transported a few kilometers and recovered in suitable habitat within reasonable times for green abalone larval development. Thus, in the absence of local brood stock, the present fishery closure is not likely to promote recovery of mainland populations of *H. fulgens* in the near future. These results underscore the importance of local current patterns and details of larval life histories to the understanding of patterns of distribution in any area.

INTRODUCTION

When animal populations are eliminated from local areas by disturbance or overexploitation, recovery depends upon recolonization by migrating adults or by dispersing larvae. If adults are sedentary, migration between isolated patches of suitable habitat may not be possible. Recolonization by larvae will depend upon the distance from spawning populations, when spawning occurs, the direction and magnitude of currents and the length of planktonic life (Scheltema 1977). Abalones, sedentary herbivores feeding largely on laminarian algae (Leighton 1966, 1971), live on rocky substrates in and around kelp forests. Rocky substrates and their associated kelp forests are irregularly distributed, especially along the mainland of southern California, among stretches of sandy coastline. Our objective was to determine the relative importance of abalone larval movement between isolated populations, particularly those on offshore islands, and larvae produced locally to the recolonization of the mainland.

Southern California populations of abalones declined considerably in recent years due to overfishing and environmental degradation (Burge et al. 1975). New regulations have reduced fishing pressure (Cicin-Sain et al. 1977) and kelp restoration projects, a sea urchin fishery and changes in wastewater management have improved abalone habitat, notably around the Palos Verdes Peninsula of Los Angeles County (Mearns et al. 1977, Wilson et al. 1977). In 1977, the California Legislature closed a section of the mainland to abalone fishing to give depleted stocks a chance to recover. We have been monitoring the changes in abalone populations on the Palos Verdes Peninsula in an attempt to understand the factors limiting recovery and to evaluate closure as a management tool.

California Department of Fish and Game landing records indicate that green abalones, *Haliotis fulgens* (Philippi), were abundant at Palos Verdes in the past. Fishing began in 1944, peaked in 1950 and ceased in 1959 in parallel with the decline of kelp forests bordering the peninsula (Wilson et al. 1977). However, green abalones are rare there today despite the restored

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presence of their algal food for almost a decade (Tegner & Butler unpubl.). Transplanted juveniles and adults and the few natives which we have found are growing well so there is no reason to assume that present environmental conditions preclude this species. The low number of native recruits in apparently suitable habitat and the relatively short green abalone larval life (Leighton et al. 1981) suggest that recolonization of Palos Verdes, an island of rocky habitat some distance from other kelp forest communities, by green abalone larvae originating elsewhere is a rare event.

Drift bottles, tubes or cards have been employed to map currents which transport larvae. Scheltema (1970, 1977) used drift bottle data to develop a general picture of the direction and magnitude of currents and to estimate the probabilities that larvae will either be retained over the continental shelf or transported across the Atlantic Ocean. Levin (1983) used drift tubes to study bay-ocean water exchange relevant to the dispersal of back bay polychaetes. Drift bottles or cards have been used previously to study water movement in the southern California Bight, often with the goal of understanding the distribution and abundance patterns of larval fishes (Tibby 1939, Schwartzlose 1963, Squire 1977). While these studies have helped to define general circulation patterns, the drifters were usually released 1 or more kilometers from shore so they are not representative of current patterns in green abalone habitat. Here we adopt a similar approach to the question of green abalone larval dispersal, releasing drift tubes directly over past and present green abalone beds during the 2 annual spawning peaks.

Two important biological parameters affecting the interpretation of drifter data are the length of the planktonic phase and the location of the larvae in the water column. The time required for green abalone larval development is temperature dependent. Trochophores hatch within 12 to 18 h at 15 to 18 °C and shortly thereafter, the larvae swim to the surface (Leighton 1974). The average duration of the swimming phase is about 9 d at 16 °C and decreases to 3.5 d at 24 °C (Leighton et al. 1981). These values reflect settlement in the continual presence of substrate; if no substrate is available, the larval phase may be prolonged. Following Jackson & Strathmann's (1981) argument that the length of the settlement competent phase is equal to or longer than the minimum precompetent period, we assumed that the maximum swimming life of these non-feeding larvae is twice the average time to settlement observed by Leighton et al. (1981).

A problem with the drift-tube approach is the question of how well tubes mimic larvae; larvae are not passive drifters. Through regulation of their vertical position for example, some larvae are able to take advantage of currents going different directions (e.g. Cronin & Forward 1979). The early developmental stages of most benthic coastal species are usually found near the surface (Scheltema 1977). The early trochophores of a Japanese abalone, *Haliotis gigantea*, are strongly positively phototactic and once at the surface, become negatively geotactic (Yano & Ogawa 1977). The phototaxicity declines with growth and disappears completely by the time the veliger stage is reached; veligers occupy the upper 10 cm of the water column day and night. By 75 h after hatching, the conclusion of this study, 80 % of the larvae were still in the upper 10 cm (Yano & Ogawa 1977). Obviously as the larvae approach settlement they must descend, but drift tubes appear to be a good model for the planktonic phase.

MATERIALS AND METHODS

We used drift tubes designed by Levin (1983) with minor modifications. Disposable, clear plastic test tubes (Falcon 2045), 15 cm long by 1.6 cm wide, were stuffed with numbered, stamped, and addressed postcards requesting the date, time and exact site of recovery. Finders were given the option of receiving information about the project and the release location of their finds; almost all exercised this option. The tubes were ballasted with fine gravel or lead shot so as to float upright in seawater with less than 2 mm of the cap above the surface. The screw-on caps were sealed with paraffin and the tubes were painted red and labeled 'OPEN ME'.

Green abalones inhabit the warmer waters of the Pacific coast, from Point Conception (about 34.5° N) to the vicinity of Magdalena Bay, Baja California (about 24.5° N) including the offshore islands (Cox 1962). To estimate the size of green abalone populations in different areas, we compiled unpublished Department of Fish and Game (Marine Resources Region, Long Beach, California, USA) block landing records of the commercial fishery. After a 43 yr closure, the mainland south of Point Conception and the Channel Is. were reopened to commercial fishing in 1943 (Cox 1962); block landing data were available for 1943 through 1974. The data show onshore-offshore and latitudinal patterns. About three-quarters of the catch was from the Channel Is. and one quarter from the mainland. Only about 1 % of the catch originated north of Point Dume on the mainland, on the northern 4 Channel Is. and San Nicolas Is. Green abalone harvests have been far higher in the warmer parts of the southern California: San Clemente, Santa Catalina, and Santa Barbara Is., Cortez Bank, and from the Palos Verdes Peninsula south along the mainland.

Additional information was gathered from published surveys (Calif. State Water Resources Control Board, 1979a–f), field biologists, commercial fishermen, others with first-hand knowledge, and our own observations. All available information was synthesized to determine where to deploy the tubes. The release sites were all within the southern California Bight (Fig. 1). The number of tubes released at each location (Table 1) was based on the relative magnitude of past and present population levels. No tubes were released at Cortez Bank because of the distance; we assume that results would be similar to releases along the west coast of San Clemente Is.

Leighton et al. (1981) report that the natural spawning period for *Haliotis fulgens* extends from late spring to mid-summer and again from early to mid-fall. We deployed 1200 drift tubes during the period of 15–19 June 1981 and an additional 1198 between 29 October and 4 November 1981. In order to cover all areas as quickly as possible, no attempt was made to standardize release times with the tides. The numbered drift tubes were released directly over known green abalone habitat from a slowly moving skiff and each location noted. Currents are greatly reduced within large forests of giant kelp *Macrocystis pyrifera* (Jackson & Winant 1983), but this does not appear to have affected these results. Along exposed coasts (all mainland and most island release sites), green abalone habitat (~ 3 to 7 m depths; Cox 1962) tends to be inshore of *M. pyrifera* forests; drift tubes apparently moved unimpeded in the band of open water between the forest and the shore. *M. pyrifera* extended virtually into the intertidal in some protected island coves but recoveries were made of tubes released both within and outside of dense kelp forests in similar times.

Water temperature was measured at each release

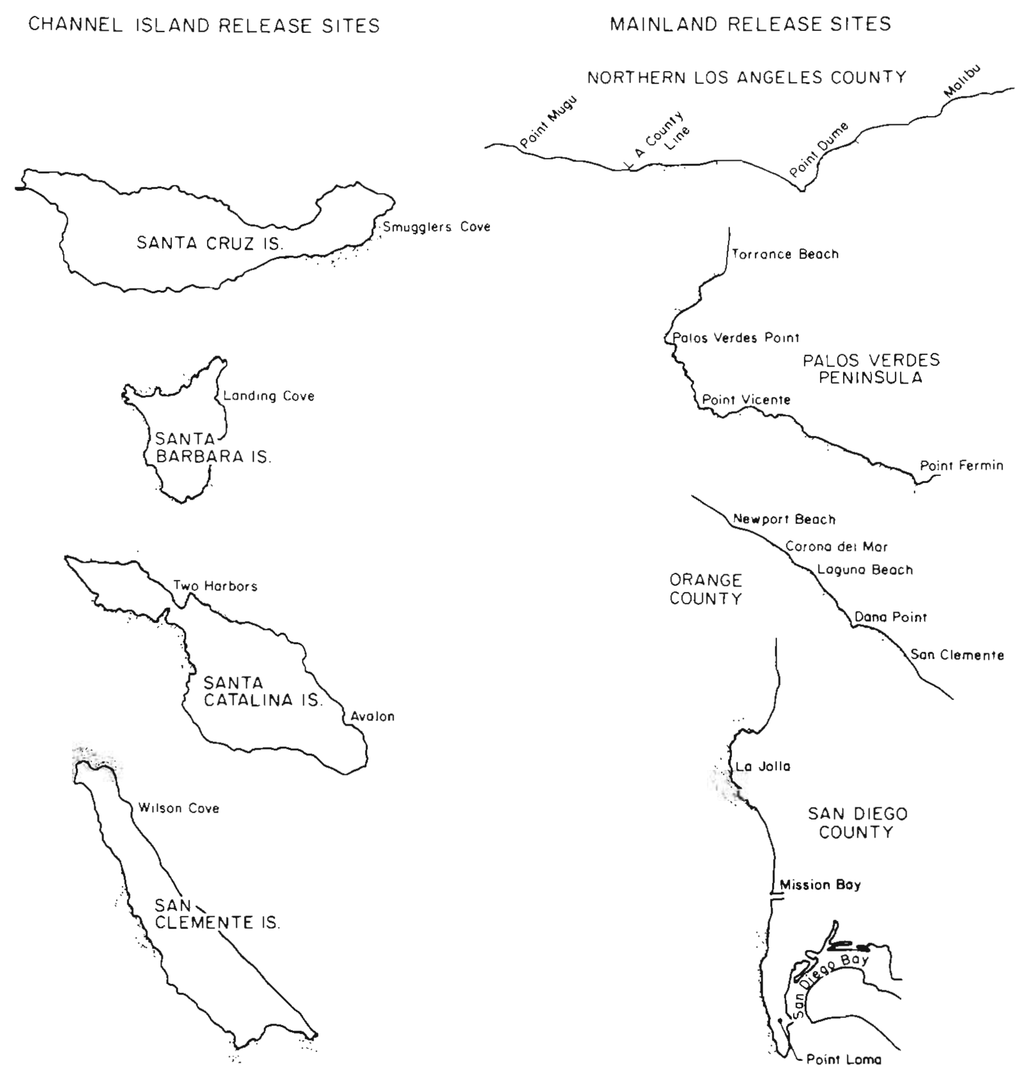

Fig. 1. Drift-tube release sites. General release areas are displayed from north (top) to south (bottom) for Channel Is. and mainland. Stippling: major green abalone habitat in each area. See Fig. 2 for correct scale and location of each area

Table 1. Drift-tube recovery rates by location and season of release

General release site	Late spring deployment		Mid-fall deployment	
	% recovery	(#found/ #released)	% recovery	(#found/ #released)
Mainland coast				
Northern Los Angeles County	52%	(52/100)	25%	(25/100)
Palos Verdes Peninsula	46%	(91/200)	19%	(40/209
Orange County	66%	(66/100)	29%	(29/100)
San Diego County	49%	(85/175)	17%	(30/174)
Coastal totals	*51%*	*(294/575)*	*21%*	*(124/598)*
Channel Island				
San Clemente Is.	7%	(13/175)	1%	(2/150)
Santa Catalina Is.	22%	(38/175)	10%	(17/175)
Santa Barbara Is.	4%	(7/175)	3%	(5/175)
Santa Cruz Is.	9%	(9/100)	2%	(2/100)
Island totals	*11%*	*(67/625)*	*4%*	*(26/600)*
Overall totals	*30%*	*(361/1200)*	*13%*	*(150/1198)*

site and mid-channel between release areas. Weather conditions were within the range of normal variability during both deployments but on 12 November 1981, 8 d after the last tubes were deployed, a storm from the northwest reached southern California. Storm conditions persisted for several days.

RESULTS

Recovery rates

Recovery rates varied with the site and season of deployment (Table 1). Return rates were about 5 times higher for tubes released along the mainland than for tubes released at Channel Is. locations for both the spring and fall deployments. The variation in return rates along the mainland reflected coastal topography. The Palos Verdes Peninsula and the Point Loma Peninsula in San Diego County, both characterized by stretches of high cliffs with limited land access to beaches, consistently had lower returns than northern Los Angeles County and Orange County where public access is easier. The largest number of insular returns was from Santa Catalina Is., reflecting both its proximity to the mainland and the population of this resort area. The other Channel Is. are sparsely populated and land access to beaches is often restricted by high cliffs. San Clemente Is. is a naval base, Santa Barbara Is. is part of the Channel Is. National Park but has few visitors, and Santa Cruz Is. is a privately owned ranch; the number of beach goers on these islands is negligible.

Recovery rates from the June deployment were 2 to 3 times higher than the fall release (Table 1), probably due to seasonal changes in current patterns as well as the number of people going to the beach. The June release was at the end of the school year and beaches were crowded; the time between drift tubes arriving at beaches and recovery was probably negligible. The number of beach goers was lower in November so delays between arrival and recovery are more likely to be important.

Transport from the Channel Islands to the mainland

Four % of the 1225 drift tubes released over Channel Is. green abalone beds were later recovered on the mainland (Table 2). Recovery sites and simple trajectories from release areas are shown in Fig. 2 & 3. The variation in trajectories suggests that much of the seasonal variation in recovery rates was due to changes in currents. For example, tubes deployed in June on the north and south ends of San Clemente Is. and on Santa Catalina Is. were recovered to the north and east along the mainland. No tubes deployed from the western side of San Clemente Is. in June and no tubes from any of the fall San Clemente Is. release areas were found on the mainland. The generally southeastern trajectories of the tubes released at Santa Catalina Is. in the fall suggest that the fall drift tubes from San Clemente Is. probably ended up far to the south in central Baja California if they washed ashore. Trajectories of drift tubes released at Santa Barbara Is. in June ranged widely from northwest to southeast along the mainland; the fall recoveries were to the southeast. There was a high recovery rate and strong eastward movement of the drift tubes released at Santa Cruz Is. in June. The single fall recovery along the mainland was to the southeast.

The mainland recovery rates of drift tubes released

Table 2. Analysis of movement for drift tubes transported from Channel Islands to mainland

Season of deployment General release area	Number recovered	% total released	Minimum # days	Average # days	Maximum transport rate ($cm\ s^{-1}$)	Average transport rate ($cm\ s^{-1}$)
Late spring deployment						
San Clemente Is.	10	6%	20	27	6.2	4.6
Santa Catalina Is.	12	7%	5	26	10.0	4.3
Santa Barbara Is.	6	3%	25	64	5.6	3.5
Santa Cruz Is.	8	8%	10	17	8.0	4.9
Mid-fall deployment						
San Clemente Is.	0					
Santa Catalina Is.	7	4%	15	53	4.7	3.1
Santa Barbara Is.	1	1%	128		1.7	
Santa Cruz Is.	1	1%	58		3.0	
Total	*45*	*4%*				

at different Channel Is. (Table 2) showed little relation to minimum distances from the islands to the mainland; e.g. San Clemente Is. is 20 km further from the mainland than Santa Barbara Is. but had twice the recovery rate for tubes deployed in June. Recovery rates are more likely a function of the directness of current patterns. Drift tubes released from Santa Cruz Is. had the highest recovery rate of the June insular

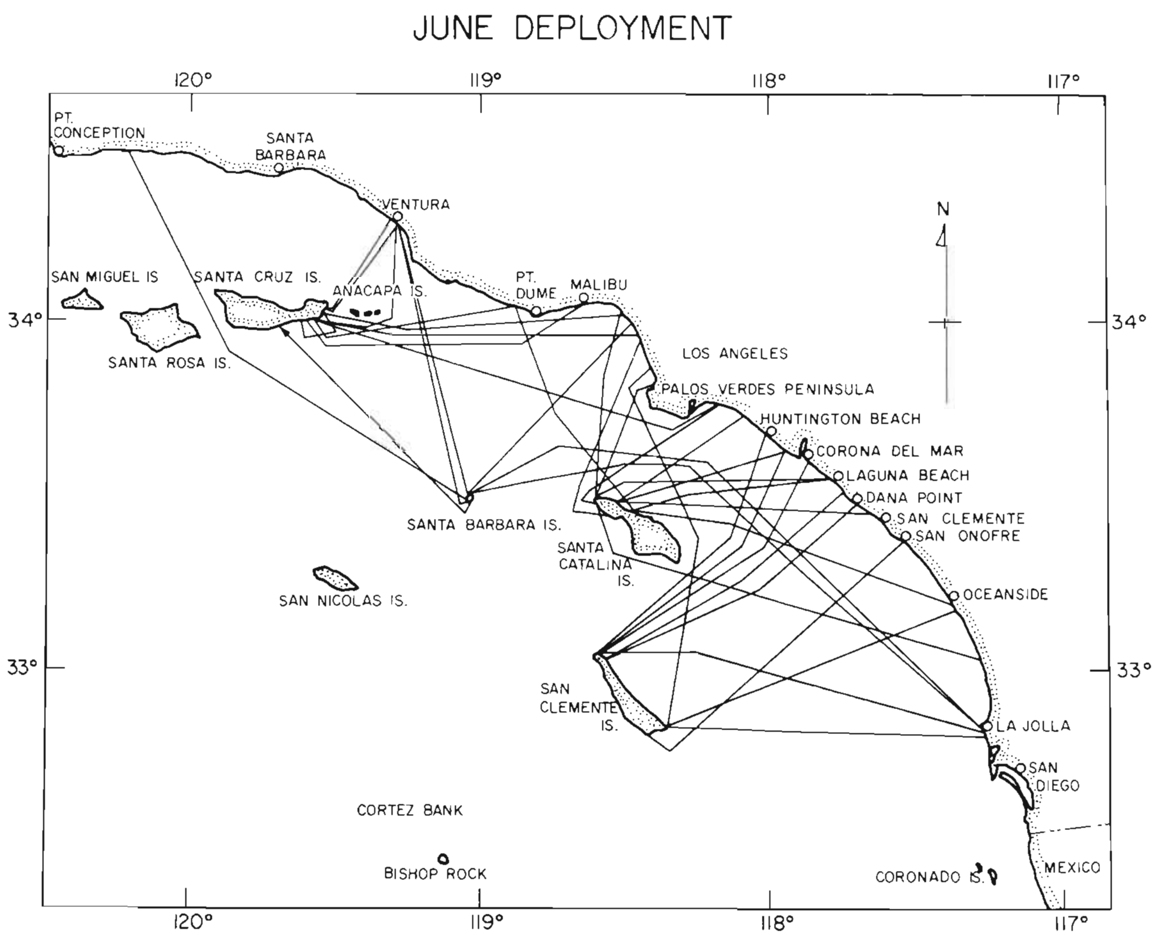

Fig. 2. Approximate routes of drift tubes from June deployment released at the Channel Is. which were later recovered on the mainland or on another island. Arrowhead: direction of inter-island movement

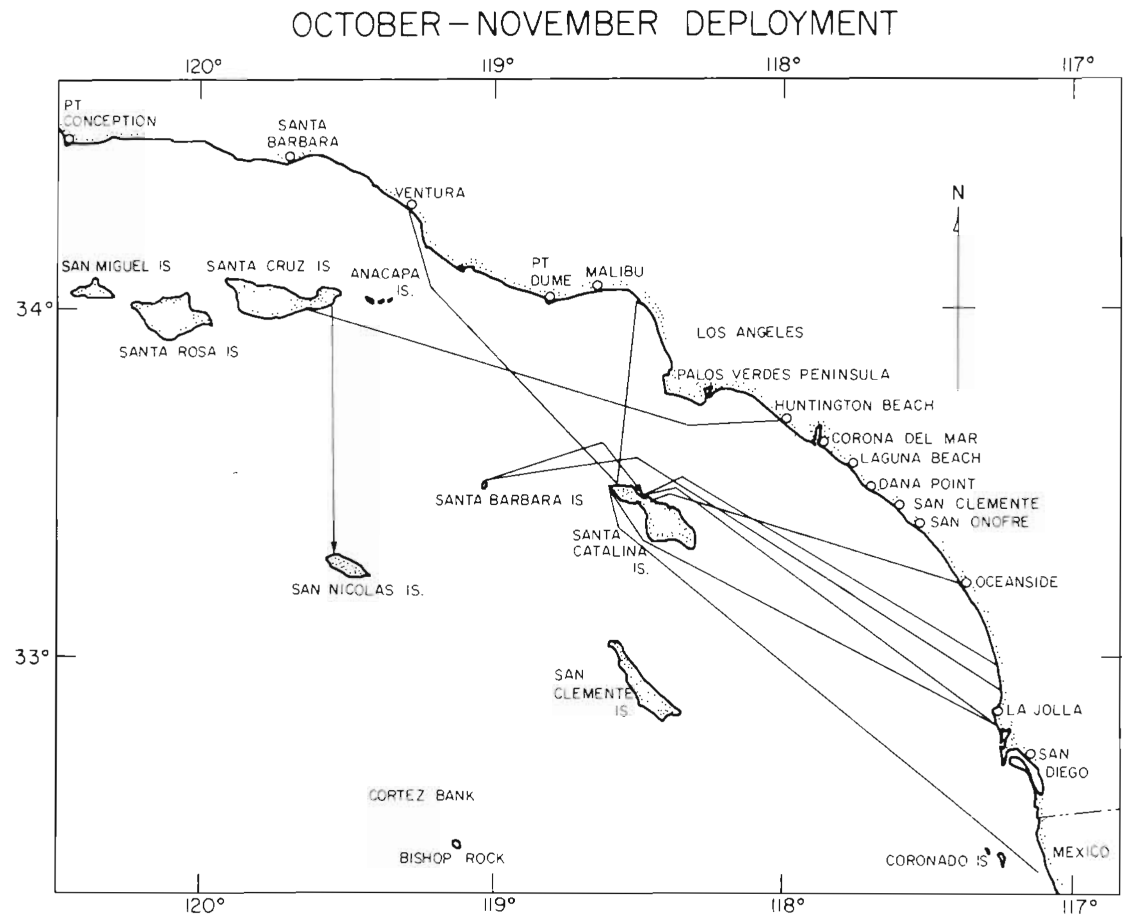

Fig. 3. Approximate routes of drift tubes from October–November deployment released at the Channel Is. which were later recovered on the mainland or on another island. Arrowheads: direction of inter-island movement

releases and also the highest average transport rate (Table 2). In contrast, Santa Barbara Is., which is only about 8 km farther from the mainland than Santa Cruz Is., had the lowest average transport rate and lowest recovery rate. The wide dispersal of tubes released on Santa Barbara Is. suggests that water motions are complex in this area; transport by eddies (e.g. Schwartzlose & Reid 1972, Owen 1980) could greatly increase the distance tubes travel.

Of the 45 island releases eventually recovered on the mainland, only 5 were found within time periods consistent with the length of green abalone larval life. The average water temperature was 21 °C in June. The average duration of the swimming period is less than 5 d at 21 °C (Leighton et al. 1981); to be conservative and allow for survival past the average time to settlement, we assumed that larvae would remain viable for 10 d. Four of the 36 tubes from the June deployment were recovered within this period. One tube from Santa Catalina Is. was found 5 d after release on the Palos Verdes Peninsula, a second tube from Santa Catalina Is. was recovered at 9 d near Huntington Beach, and 2 tubes from Santa Cruz Is. were found at 10 d, 1 in Ventura and 1 near Point Dume (Fig. 2). Only 2 of the 4 recoveries within an appropriate time period, those at Palos Verdes and Point Dume, were near green abalone habitat. The average recovery time was 27 d for tubes released on San Clemente Is., 26 d for Santa Catalina Is., 64 d for Santa Barbara Is. and 17 d for Santa Cruz Is. (Table 2).

At the fall average temperature of 16.6 °C, the average duration of the green abalone larval swimming period is about 8 d; we assumed that larvae would be viable for 16 d. One tube from Santa Catalina Is. was recovered 15 d later in Santa Monica, a sandy beach east of Malibu (Fig. 3). The elapsed times for the 8 other island tubes deployed in the fall and later recovered on the mainland were considerably beyond the realm of feasibility for green abalone larval life (Table 2).

Transport within and between Channel Islands

A number of drift tubes were recovered on the same island as they were deployed, at distances ranging from less than 1 to 18 km from their release sites and times ranging from the same day to several months later. These included 36 tubes from relatively populated Santa Catalina Is., 4 from San Clemente Is., 3 from Santa Barbara Is. and 1 from Santa Cruz Is.

Three tubes are known to have been transported between islands. In June, 1 tube deployed at Santa Barbara Is. was found on Santa Cruz Is. (Fig. 2). In the fall, 1 tube released on Santa Barbara Is. was recovered on Santa Catalina Is. and 1 tube from Santa Cruz Is. was found on San Nicolas Is. (Fig. 3). The time lags before recovery were quite long but, given sparse human use of these beaches, these data are important for showing that transport between islands does take place.

Transport within and between mainland release areas

About 36 % of the drift tubes released along the mainland were recovered. Recovery was defined as local if it was within 1 km of the boundaries of a general release area (Table 3). Drift tubes released in northern Los Angeles County had the highest tendency (90 %) to remain within the boundaries of any of the 4 general release areas; Orange County tubes had the greatest tendency (52 %) to leave, generally to the long stretch of sandy coastline between San Onofre and Oceanside. The direction of transport varied seasonally; downcoast transport was predominant particularly in the spring but upcoast transport increased in importance in the fall, especially at Palos Verdes. Comparing average times to recovery with water temperatures at the time of deployment (Table 3), most of the recoveries of mainland releases were within an appropriate time frame for green abalone larval development.

Of the general mainland release areas, drift tubes released near Palos Verdes were recovered over the widest range (Fig. 4). Many tubes from the June deployment travelled considerable distances to the southeast; some were recovered in Orange and San Diego County release areas and in inappropriate habitat between. One June tube was found in Mexico, 220 km from its release site. One fall release was recovered on Santa Catalina Is. and another on the eastern edge of the northern Los Angeles County release area. The average time to recovery was 7.5 d in June and 9.4 d in the fall (Table 3). The predominant direction of transport was downcoast in June an average distance of 46 km and upcoast a mean of 12 km in the fall.

The origins of the drift tubes recovered within the boundaries of each general release area along the mainland are summarized in Table 4. The northern 2 mainland sites had the least input from other release sites; Orange and San Diego Counties, apparently due to their southeasterly location in the bight, had the most input from other release areas, both island and mainland. A total of 66 drift tubes was recovered on the Palos Verdes Peninsula; 1 was from Santa Catalina Is., 1 was from northern Los Angeles County and 64 were

Table 3. Analysis of movement for drift tubes released along mainland

General release area / Date of deployment	Total # recovered	% tubes* remaining within local release area	% tubes travelling to other general release areas	% tubes recovered in inappropriate habitat between general release areas	Average** time to recovery (d)	Water temperature at release (°C)	% recovered* downcoast	Av. distance travelled (km)	% recovered* upcoast	Av. distance travelled (km)	% recovered inshore	% recovered offshore
Northern Los Angeles County												
Late spring	52	87	2	12	3.5	21	48	13	17	3	35	0
Mid fall	25	92	0	8	11.1	15	48	2	24	3	28	0
Palos Verdes Peninsula												
Late spring	91	42	9	49	7.5	22	70	46	21	3	9	0
Mid fall	40	68	5	27	9.4	15	20	3	60	11	18	3
Orange County												
Late spring	66	44	0	56	4.6	23	94	22	2	2	5	0
Mid fall	29	52	0	48	7.7	16	59	23	27	8	14	0
San Diego County												
Late spring	85	64	0	36	3.9	23	61	9	33	7	6	0
Mid fall	30	70	0	30	7.6	17	57	9	43	3	0	0

* Because of rounding errors totals may exceed 100%
** Excludes tubes found more than 2 mo after release

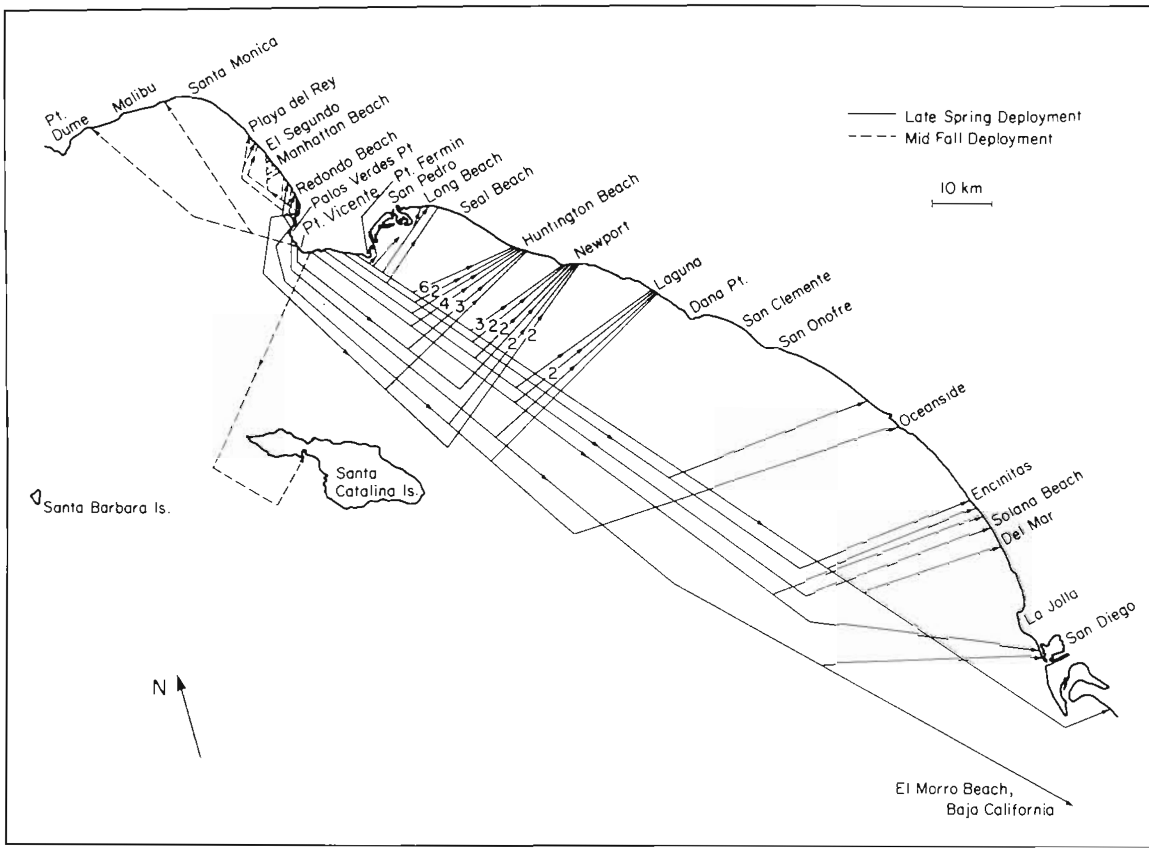

Fig. 4. Approximate routes of drift tubes deployed on Palos Verdes Peninsula later recovered at locations off the peninsula

deployed on the Palos Verdes Peninsula itself. Most of the 64 travelled up to several km from their release site; 14 were recovered directly inshore (Fig. 5). The average time to recovery for tubes released and recovered on the Palos Verdes Peninsula was 6.7 d in the spring and 10 d in the fall.

Analysis of the returns from Palos Verdes by area of release indicates that there was considerable variability in the tendency of the tubes to remain on the peninsula in appropriate habitat. Of the tubes released from the central area to the northern boundary, 56 % of the recoveries were found on the peninsula compared to 29 % of the tubes released in the eastern third of the peninsula. The highest proportion (66 %) remaining in the area were released between Palos Verdes Point and Torrance Beach, the northern sector of the peninsula which faces into Santa Monica Bay. A similar high rate and upcoast recovery pattern was found for tubes released from the northern portions of Point La Jolla.

DISCUSSION

Perhaps ideally the study of larval dispersal should be based on direct sampling of the plankton. However, the logistical considerations of sampling short-lived

Table 4. Origin of drift tubes recovered within the boundaries of each general release area

General release area	Total # tubes recovered in general release area	% originating* locally	% originating from other mainland sites	% originating from Channel Is. sites
Northern Los Angeles County	76	95	1	4
Palos Verdes Peninsula	66	97	2	2
Orange County	55	80	9	11
San Diego County	83	90	2	7

* Because of rounding errors totals may not equal 100 %

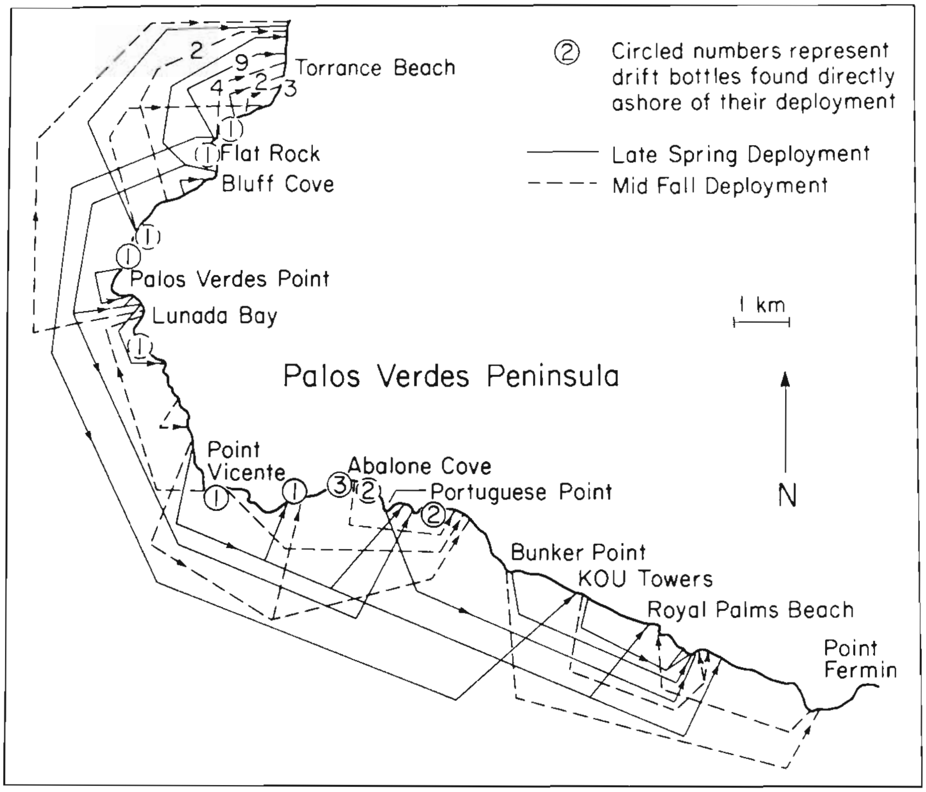

Fig. 5. Approximate routes of drift tubes deployed on Palos Verdes Peninsula recovered on the peninsula

larvae which are patchy in time and space and the identification problem – there are 7 species of *Haliotis* in southern California (Cox 1962) and no larval key – make plankton studies impractical. Drifter data can offer useful information on nearshore surface currents but the results must be interpreted with caution; whereas the points of release and recovery are known, the actual route travelled and the time on the beach before recovery can only be inferred (Schwartzlose 1963). In densely populated regions with well-used beaches such as the southern California mainland, however, drifters can provide accurate information about short term rates and probabilities of surface transport between sites (Levin 1983).

The overall drift-tube recovery rate for this study was 21.4 %, including 7.6 % of the tubes released at the Channel Is. and 35.7 % of the tubes deployed along the mainland. The observed recovery rate of tubes deployed near the islands is similar to the 3.2 % (Tibby 1939), 3.4 % (Crowe & Schwartzlose 1972) and 5.7 % (Squire 1977) recovery rates in southern California studies where drift bottles and drift cards were released in offshore grids. Most returns from these synoptic grids have been drifters released within 32 km of shore (Schwartzlose 1963). Only Santa Catalina Is. is this close to the mainland and it had the highest recovery rate (Table 1).

Because of the generally low number of visitors and inaccessibility of many of the island beaches, we did not expect to obtain much information about drift tube transport within and between the islands. The data from relatively populated Santa Catalina Is. indicate that, at least for the larger islands, spawning is likely to contribute to green abalone populations on the same island. Whether larvae spawned on the 2.5 km long Santa Barbara Is. can remain there long enough to complete development is not known. Drift tube transport was observed between 3 islands; the recovery times were long but the data do suggest that insular spawning may contribute to populations on other islands. In contrast, the high recovery rates along the mainland suggest that we can draw conclusions about the relative importance of local *vs.* off-site spawning to mainland populations.

Fishery statistics show that the major green abalone populations of California are on the offshore islands. The important question for the recovery of depleted mainland populations is whether current patterns are appropriate for transporting significant number of larvae from the islands to the mainland within the time frame set by the green abalone larval life span. The drift tube data from 1981 suggest that the islands are not contributing importantly to mainland populations. Of the drift tubes released near the islands, 4 % were later recovered on the mainland and of these, only 5 or 0.4 % of the total deployed were recovered within an appropriate time span as indicated by prevailing water temperatures, and of these, only a portion were found near suitable habitat. The average recovery rate of tubes released along the mainland was 36 %, so if we assume a 36 % recovery rate of island releases along the mainland, this would raise the probability of dispersal from the islands within an appropriate time period to about 1.1 %. Even if we double this value to allow for the unknown time tubes may have lain on beaches before recovery, it is apparent that local sources of larvae are more important to mainland populations than the few larvae which successfully cross the channel. Thorson (1961) noted the possibility that aggregations of larvae could be transported as swarms. Such a behavioral adaptation could increase the significance of the low rate of drift tube transport from the islands to the mainland. However, the severely depleted green abalone population on the Palos Verdes Peninsula today (Tegner & Butler unpubl.), despite almost a decade of restored food availability (Wilson et al. 1977), suggests that the drift tube results for 1981 are not atypical and offers no evidence for larval swarms.

These observations are consistent with the general surface circulation in the southern California Bight as developed by drift bottle and drogue studies and observations from the California Cooperative Oceanic Fisheries Investigation (Schwartzlose 1963, Schwartzlose & Reid 1972, Owen 1980). The main body of the California current generally flows south from Point Conception, offshore of the Channel Is. Circulation in the Channel Is. area is complex and often characterized by eddies of many sizes. Prominent features of the inshore circulation include the southern California eddy, a large cyclonic gyre generally centered over the Santa Rosa Is.-Cortez Bank Ridge, and flow to the southeast only very nearshore during most of the year. The eddy is usually not present during March, April and May; during this time the general direction of the flow is to the southeast throughout the bight. The influence of the southern California eddy on most of the June island releases is illustrated in Fig. 2; the eddy effect was less apparent but still present on the fall island releases (Fig. 3). Hendricks (1979) noted that quasi-permanent eddies in the coastal flow field are likely in embayments. Major exceptions in the generally downcoast transport of drift tubes along the mainland were found where the northern end of the Palos Verdes Peninsula faces into Santa Monica Bay and where the northern portion of La Jolla faces into the La Jolla Bight. In the latter case we have anecdotal evidence that the drift tubes are behaving similarly to larvae. Several tubes from northern La Jolla (where green abalones are common in a shoreline preserve) were recovered near Scripps Institution of Oceanography. Green abalones settled in the seawater system of one of the laboratories drawing seawater from the Scripps Pier in 1981 (D. Hanan, D. Leighton & A. McCall, pers. comm.).

The feature of the nearshore circulation probably most important to the dispersal of green abalone larvae between populations along the mainland is what Schwartzlose (1963) describes as flow to the southeast very near shore at times when the eddy is present. Long-term averages of long shore currents measured near San Diego are to the south near the surface in all seasons (Winant & Bratkovich 1981). This could allow larval transport downcoast between isolated areas of suitable habitat. One drift tube from northern Los Angeles County out of 77 (1.2 %) recovered from that general release area was found on the Palos Verdes Peninsula 3 d after its June release. Five tubes (4 %) released at Palos Verdes in June were recovered in appropriate habitat in Orange County in an average of 7.6 d and 2 (2 %) in San Diego County in 11.5 d. Tubes from Orange County were recovered downcoast but none as far as the San Diego release area. In the fall, 1 tube (1 %) from Palos Verdes travelled northwest into the northern Los Angeles County release area and was recovered 8 d after deployment. Thus average times to recovery were within the range of green abalone larval dispersal. While these results do indicate the possibility of larval dispersal between mainland release areas, its importance is a function of present population sizes. All 4 areas supported green abalone populations in the past but presently adults are rare in the northern 3 areas; only San Diego County has an appreciable breeding population (Calif. State Water Resources Control Board, 1979a, b, c; pers. obs.). Winant (1980) notes that tropical storms, which generally occur once or twice a year between mid and late summer, may induce strong currents to the north along the narrow southern California shelf. While such events could help repopulate areas north of San Diego, most storms in this region occur during the winter when green abalones are not breeding. Along the shelf, surface transport may also be affected by tidal currents (Winant & Olson 1976) and slicks associated with tidally-driven internal waves (Shanks 1983).

The season of spawning, as well as the length of larval life, may also be an important determinant of colonizing ability. Red abalones, *Haliotis rufescens* (Swainson) can be found in spawning condition during the entire year (Young & DeMartini 1970, Leighton 1974). Current patterns vary seasonally (e.g. Schwartzlose 1963), so an animal with a long spawning season has more potential for larval transport in different directions than one with a short spawning season. This was illustrated by drift tubes released at the mouth of Mission Bay in San Diego (Levin 1983), a site near substantial populations of both red and green abalones. In February 1980, a storm carried drift tubes from Mission Bay to Palos Verdes in 1 wk. In May and August, however, the longest distances travelled to the north were 2 and 5 km respectively (Levin 1983). Pink abalones (*H. corrugata* Gray) have essentially the same spawning season as green abalones (Leighton 1974). All 3 species are present on some offshore islands but red abalones are most likely to be spawning during the March–May period when the southern California eddy disappears and flow to the southeast could transport larvae from the islands to the mainland. The hypothesis that red abalones are better long-distance colonizers than the other 2 species as based on the differences in spawning season offers an explanation of present abalone populations on the Palos Verdes Peninsula. Department of Fish and Game records indicate that green and especially pink abalones were considerably more abundant than red abalones before the decline of abalone populations in the 1950's. Today red abalones are much more numerous than these congeners (Tegner & Butler unpubl.).

The mainland between Palos Verdes Point and Dana Point was closed to both commercial and sport abalone fishing in 1977 to allow recovery of depleted stocks. Our results suggest that in the absence of local brood stock, a fishery closure alone will not be an effective management policy for the recovery of mainland populations of green abalones in the near term future. Relatively nearby Channel Is. have good breeding populations but the drift-tube data suggest that currents during the spawning season are inappropriate for much larval transport to the mainland within a suitable time frame for green abalone larval survival. The transport times between mainland sites are appropriate but only a small number of drift tubes travelled between these sites. However, high proportions of the drift tubes deployed in each general release area were transported a few km and recovered in suitable habitat within reasonable times for green abalone larval development. To provide local sources of larvae we, in conjunction with the Department of Fish and Game, have established experimental transplants of reproductively-mature animals in areas of the Palos Verdes Peninsula where the drift tube data suggest that resulting larvae are most likely to contribute to green abalone populations on the peninsula. Subsequent monitoring for recruitment success should indicate the efficiency of this approach.

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