THE INTRODUCTION AND ESTABLISHMENT OF *ACANTHOPHORA SPICIFERA* (VAHL) BOERG. AND *EUCHEUMA STRIATUM* SCHMITZ IN HAWAII

Define DIF (Diffusion Index Factor) – a measure of water motion

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ABSTRACT

Two introduced algal species, Acanthophora spicifera (Vahl) Boerg. and Eucheuma striatum Schmitz, were studied regarding their ecology in Hawaii. This study was undertaken to resolve the role of man in their dispersal, to determine the physical and biological factors defining the limits of their distribution, to discern associations and competition with other algal species and to find out whether their introduction resulted in any immediate effects on reef animals.

Acanthophora was found on five of the six main Hawaiian Islands (Kauai, Oahu, Molokai, Lanai, Maui), but was not present on Hawaii. Seventeen of the 21 harbors investigated had A. spicifera in them. It was found that many thalli had colonized the hulls of ocean going boats. The rapid spread of A. spicifera throughout the Hawaiian Islands may have been facilitated by its ability to colonize boat hulls.

Why not Hilo, Kawaihai or KONA?

A distinctive distribution pattern of A. spicifera was observed: it was present on those shores where the Diffusion Index Factor (DIF), a measure of water motion, was DIF 53, but was missing from those shores where the water motion was significantly higher (DIF 79). It was also found in areas on coral reefs where the water motion

was DIF 13-64, but not where the DIF was 82. Data from experiments and transect studies support the conclusion that the water motion limits of Acanthophora were between DIF 10-76.

Neither depth, light, substratum type, proximity to municipal pollution or salinity correlated significantly with its growth, seasonality or abundance, but Acanthophora grew significantly better in water temperatures of 24.0°C - 27.0°C. This temperature range may limit the distribution of Acanthphora to tropical and subtropical seas.

Acanthophora spicifera occurs with Ahnfeltia concinna J. Ag. and Ulva fasciata Delile on basaltic rock in areas of strong wave action and it occurs with Laurencia nidifica J. Ag., Gracilaria coronopifolia J. Ag., Hypnea cervicornis J. Ag., Sargassum spp. and Valonia aegagropila C. Ag. on amalgamated coral rock in areas of moderate wave action. Acanthophora is often attached to L. nidifica on the reef and when this occurs, the larger A. spicifera thalli dominate L. nidifica. However, in controlled experiments using equal amounts of both species, the growth of both appeared to be suppressed.

The distribution of Eucheuma striatum in Kaneohe Bay during May 1976, was nearly the same as the pattern in which it was originally planted in November 1974.

Eucheuma was contained in an area less than 50 m from Coconut Island by deep calm water unsuitable for its survival. It lacked the ability to disperse over shallow depressions (1-2 m deep) and colonize neighboring reefs without the help of man. Depth was the single most important physical factor limiting its dispersal.

There was a total fresh weight standing crop of 21-24 metric tons of *E. striatum* on a 500 m long section of reef edge from December 1976, to June 1977. When protected from grazing, its growth rate at this location was 5.0%/day. However, the total standing crop decreased to 7.5 tons in December 1977, and by May 1978, only traces of thalli remained. This entire crop was only a temporary accumulation of unattached fragments that were slowly slipping into deeper water where they died. These data supported the conclusion that the population on the reef edge was only being maintained by a steady influx of thallus fragments that escaped from the wire pens enclosing experimental plantings of *Eucheuma*. When these experiments were removed, the population could not maintain itself and soon disappeared.

Eucheuma had entered a portion of the reef not occupied by other large algae. Consequently, it appeared to be the basis of a community richer in species than adjacent reefs. Even though its growth was limited by severe fish

grazing, it did provide food and shelter for the fish and a substratum for numerous invertebrates. Eucheuma did not attach to coral heads, but small corals died soon after being covered by thalli. Implications concerning the ecological effects of introduced algae are discussed in light of these data.

SUMMARY

Two strikingly different alien red algal species have been studied regarding their introduction, dispersal, establishment and effects on other marine organisms in Hawaii. *Acanthophora spicifera* was the primary species of this study followed by *Eucheuma striatum*.

The introduction of Acanthophora spicifera

The conclusion that *A. spicifera* was introduced to Hawaii by means of a barge in 1950 (Doty, 1961), has been tentatively accepted as the starting point for the present research.

Early collections of *Acanthophora* were not from ports or areas near ports that were distant from each other. This indicates that the alga was probably well established in a variety of locations by the time it was discovered in Pearl Harbor.

Nevertheless, *Acanthophora* inhabits ports and is thus available to colonize ship hulls. It was present in 17 of the 21 harbors examined during the study and was found attached to the hulls of numerous ocean going boats that frequently travel between Hawaiian ports. Ships probably provided an easy and rapid means by which the alga was dispersed throughout the islands after its initial introduction.

Physical factors defining Acanthophora's distribution limits

Acanthophora was found in the same general habitats in Hawaii as were described for it in the literature, but the distribution pattern of Acanthophora appeared to be more closely related to water motion than to substratum type, salinity, temperature, depth or other physical factors. The substratum types upon which Acanthophora grows are highly varied, calcarious and igneous rock, cinder bricks, ropes, rubber bands, buoys, ship hulls, worm tubes and other algae. It is found in habitats with a salinity of 19-36 o/oo and is probably not affected by seasonal rains. There was no significant difference in the temperature of the water between the shore lines where Acanthophora was found and where it was not found. However, the temperature range in which Acanthophora occurs may be very important in limiting its global and seasonal distribution. The optimum growth for Acanthophora in Hawaii was limited to within about 25-27°C, although some growth was occurring below 24°C. Trono's hypothesis concerning the temperature range of Acanthophora was modified by stating that Acanthophora is limited to water that remains between 24-28°C.

Big Is. coldwater discharge from springs?

NOTE - Palaau flats get way over 27°C

The depth factor was separated from the water motion factor at the KMCAS transect. This transect is unique because the reef is essentially flat and the dominating feature is the rush of water that flows across the reef. Light too, was eliminated as a factor since there was no detectable difference in light intensity with depth. The seaward limit of *Acanthophora* at this transect corresponded significantly with a water motion value of DIF 75.6. Water motion was the most important physical factor across the reef at KMCAS effecting the growth of *Acanthophora*.

What about water motion across the bottom of a ship or barge?

Water motion may also be the factor that results in the distinctive distribution pattern of *Acanthophora* on the shore lines of the islands. There was a significantly higher water motion value (DIF 78.9) on those shores without *Acanthophora* than on those shores with it (DIF 52.8). The higher value also corresponds closely to the mid-point between the DIF values at 25 m and 30 m at the KMCAS transect (DIF 75.6). It is concluded that the upper limit of *Acanthophora*'s tolerance to water motion is about DIF 76 and the lower limit is about DIF 10. The outer or offshore limit of its population may be a good indicator of rapid water motion (DIF 75-80) and the inner or near shore limit of its population may be a good indicator of low water motion of about DIF 10.

Interactions with native algae

Interactions between *Acanthophora* and other algae were investigated and a clear, consistant and intimate association with *Laurencia nidifica* was found. *Laurencia nidifica* was commonly found growing attached to Acanthophora thalli and there is evidence that this same association occurs elsewhere in the world. Laurencia was often found attached to Acanthophora and inadvertently pressed onto herbarium sheets by investigators in other countries. This association has not been described before, but it is probably more than just a matter of the two algae being in the same general habitat at the same time. It appears that the closeness of the association between the invader and the previously established alga, L. nidifica, was a result of a unique compatibility and similar growth requirements.

From the transect data gathered it appears as if A. spicifera may be suppressing the growth of L. nidifica. It also appears that Acanthophora has invaded the space between Valonia and Sargassum on the reef at KMCAS. This space was probably once occupied by L. nidifica, but is now utilized by Acanthophora.

Competition betweeen A. spicifera and L. nidifica was tested experimentally in water trays and in the field. In each of the experiments there was a tendency for the growth of both species to be suppressed when they were grown in contact with each other. Such a suppression is an indication of competition according to other authors. However, this suppression was not statistically significant.

Acanthophora has also displaced Hypnea cervicornis on certain reefs, but in a different way than just described for *L. nidifica* at KMCAS. When *A. spicifera* came to Hawaii it formed an association with *L. nidifica* and since it grows taller than *L. nidifica*, *H. cervicornis* became entangled in the branches of *Acanthophora*. This displaced *H. cervicornis* higher in the water column than before.

The invasion of the reef at HIMB by *A. spicifera* has increased the carrying capacity of the reef by providing additional surface area for the growth of epiphytes. *Acanthophora*, unlike the local algae, utilizes tube worms as a substratum and is in turn a host for *H. cervicornis*, which would have been only a trace species in this community without the alien alga.

Does this happen at Kawela on Molokai, where at Kamalo there were huge drifts of Acanthophora?

Introduction and dispersal of Eucheuma

The particular morphological form of *Eucheuma striatum* in this study was just one of several *Eucheuma* variations that was brought to Hawaii between 1970 and 1980. It was shipped directly from the Philippines to Honolulu on 9 September 1974. The present research has either partially or wholly answered the following three questions concerning this species. (1) How far will this alga spread before being checked by environmental factors? (2) Will it become as widespread in Kaneohe Bay as *A. spicifera*? (3) What effects will it have on other marine organisms?

Eucheuma did not have the ability to cross shallow

TABLE 1.--Physical features of the locations surveyed for the presence of Acanthophora spicifera in Hawaii.

Location	Salinity ‰	Temperature °C	DIF
OAHU ISLAND			
Kaupo	35.0	25	66.5 ± 5.9
Waimanalo	35.0	24	74.2 ± 1.0
Lanikai	35.0	28	58.8 ± 2.6
Kailua	35.0	28	62.5 ± 15.4
Kokokahi	35.5	28	36.8 ± 0.3
Lilipuna Pier	35.0	28	45.0 ± 1.2
Waiahole	19.5	28	56.6 ± 3.1
Kaaawa	35.5	27	65.6 ± 3.5
Swanzy	35.5	27	53.7 ± 4.3
Punaluu	35.0	25	50.3 ± 2.3
Hauula	35.6	25	48.9 ± 2.3
Kuhuku	35.6	25	96.7 ± 6.3
Kawela	23.9	23	55.2 ± 4.5
Pupukea	34.2	25	Lost
Kawailoa	33.1	25	57.6 ± 4.7
Haleiwa	35.0	26	51.0 ± 1.8
Waialua	35.0	26	----
Mokuleia	34.3	25	43.7 ± 1.6
Kaena	35.0	25	52.8 ± 2.7
Kaneana	35.5	25	Lost
Makaha	35.5	25	88.1 ± 8.0
Pokai Bay	35.0	26	46.5 ± 1.8
Uluhi	35.5	26	91.4 ± 9.0
Nanakuli	35.5	26	77.6 ± 4.7
Kahi Point	35.5	32	61.3 ± 7.3
Nimitz	35.0	28	----
Pearl Harbor	35.0	28	----
Sand Island	35.0	28	49.0 ± 2.5
Kewalo	35.0	28	70.4 ± 1.0
Ala Moana	35.0	28	----
Waikiki	35.0	28	66.4 ± 2.6
Diamond Head	35.5	28	80.6 ± 1.9
Waialae Park	35.0	28	52.7 ± 2.1
Wailupe Park	35.2	28	40.6 ± 4.5
Kuliouou Park	36.0	28	43.8 ± 1.6
Koko Head Park	35.0	25	84.4 ± 4.5

TIME OF YEAR?

TIME OF YEAR MAKE A DIFFERENCE?

NOT GROUNDWATER?

BY SPRING

WARM DISCHARGE

TABLE 1.--(Continued) Physical features of the locations surveyed for the presence of <u>Acanthophora</u> <u>spicifera</u> in Hawaii.

Location	Salinity ‰	Temperature °C	DIF
KAUAI ISLAND			
Haena	34.0	25.5	----
Hanalei	28.0	21.0	----
Anini	35.0	22.0	----
Moloaa	34.0	22.0	----
Hauola	34.0	21.5	----
Ahukini	34.0	22.0	----
Kalapaki	34.0	22.0	----
Poipu	35.0	25.5	----
Port Allen	35.0	23.0	----
Kikiloa	34.0	23.0	----
MOKOKAI ISLAND			
Pohakuloa	35.0	22.0	----
Kamalo	34.0	23.0	----
Kaunakakai	34.0	24.0	----
Kepuhi	35.0	22.0	----
Halawa	35.0	22.0	----
LANAI ISLAND			
Federation Camp	35.0	28.0	----
Manele Bay	34.0	27.0	----
Kamalapau	35.5	22.0	----
MAUI ISLAND			
Kahului	32.0	26.0	----
Hookipa	35.0	25.0	----
Hana	32.0	25.0	----
Maalaea	35.0	26.0	----
Launiupoko	35.0	28.0	----
Lahaina	35.0	28.0	----
HAWAII ISLAND			
Laupahoehoe	35.0	25.0	----
Hilo Harbor	30.0	23.0	----
Leleiwi	33.0	23.0	----
Honaunau	35.5	26.0	----
Kailua-Kona	35.0	26.0	----
Kawaihae	35.0	25.0	----
Kalapana	34.0	24.0	----

LOW °C FROM SPRING DISCHARGE? OR WINTER?

RIVER?

why so cold ??

SEEMS LIKE THERE SHOULD BE SOME REAL COLD SPOTS FROM SPRINGS

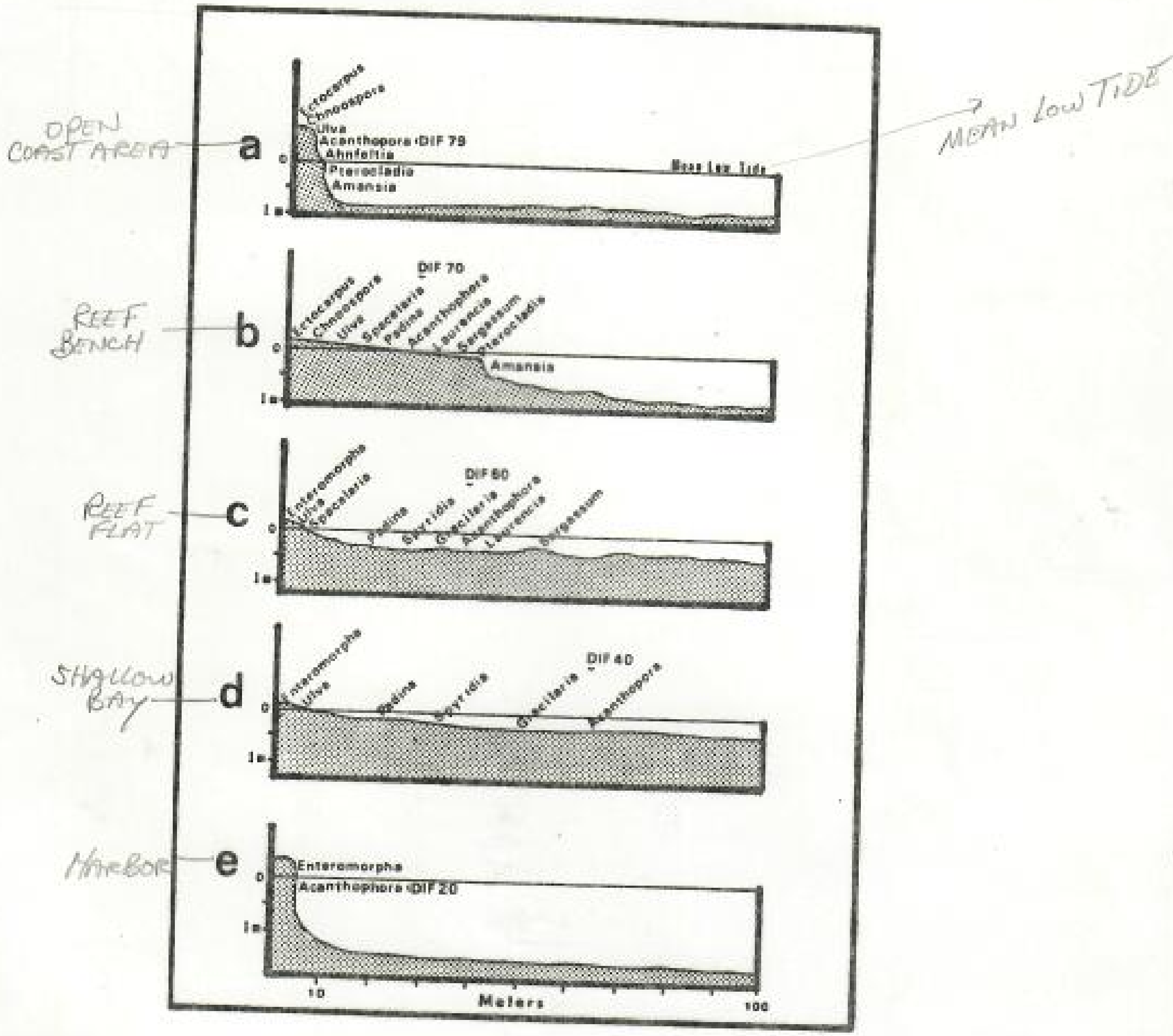

Figure 16: A summary of the basic habitats where Acanthophora spicifera is found and its position relative to the common algae found with it and to the average water motion, given in Diffusion Index Factor (DIF) values, based on data in Tables 1, 3, 5 and 15, (a) open coast area, (b) bench reef, (c) reef flat, (d) shallow bay, (e) harbor.

species (Silva, 1962). These distribution patterns are fairly stable today (MacArthur, 1967) and are often explained on the basis of past changes and subsequent stabilization of ocean currents.

Depth, distance and time are three barriers to the dissemination of algae that are also constantly present. Most of the ocean floor is deeper than the photic zone and when any propagule sinks to the depths it is lost. Briggs (1974) has shown that the Atlantic Ocean barrier and the East Pacific Ocean barrier are 91-94% effective in preventing the dispersal of marine animal species. Distance and time are interconnected since a propagule may be viable for only a given time (Carlquist, 1965), beyond which it is unable to germinate. Algal spores, like seeds or larvae, must endure prolonged periods of time in the open ocean, and survive conditions that may be unfavorable to their growth before contacting habitable substrata.

Summary

1. Barriers are obstacles to dispersal or normally uncrossable obstructions.
2. The most formidable barriers to marine species are land, temperature, currents, depth, distance and time.
3. The continents are the most effective obstacles to algal dispersal from east to west.
4. Temperature acts as an effective barrier to algal migration north or south.

5. Currents are often barriers to dispersal by carrying propagules away from suitable habitats.
6. The substrata in mid-ocean are below the photic zone and marine algae must cross such depths before reaching suitable shallow areas in the photic zone.
7. Both the distance between suitable habitats and the time necessary to reach these areas act as barriers to the dispersal of algal propagules.

Hypotheses

1. Viable marine algal propagules, ordinarily produced near the continents, would be expected to occur in some form in mid-ocean.
2. Benthic marine algal propagules, foreign to the Hawaiian Islands, but native to the continents would be expected to arrive in Hawaiian waters but at a very low rate.

Natural Transport of Algae Across Barriers

Barriers are sometimes crossed by algae when they are carried by various natural agents, such as rare meteorological phenomena, or animals such as birds, insects, seals, whales, turtles, fish, shrimp or snakes. Any of these agents can be expected to disperse algae into new locations.

Dispersal of higher plants to the Hawaiian Islands from the continents by wind has been discussed by Carlquist (1965; 1970), however, there is also a possibility of at least short distance transport of heavy objects by this same means. Algal mats up to 56.8 g have been collected "from the sky" (Maguire, 1963) and seventy-eight instances of fish weighing up to 4.6 kg have been recorded (Bajkov, 1949) as falling from the sky long distances from their habitat. Strong winds may, in rare cases, carry algae into new locations.

Birds and insects have been very effective agents in the introduction of many species to Hawaii. There is an ever increasing list of foreign birds that have arrived in Hawaii from as far away as Alaska and South America (Carlquist, 1965). Many of these ingest algae (Maguire, 1963) and carry propagules easily for hundreds of kilometers (Proctor, 1959). Similarly, insects such as Odonata (Parsons, et al., 1966), Diptera and Lepidoptera (Sides, 1971; Revill et al., 1967) will transport small algae up to 386 km over land possibly into new locations.

Seals also provide a means of transport for various algae. Pringsheimiella scutata (Reinke) Schmidt and Petrak, grows on the pelage of the Hawaiian monk seal (Monachus schauinslandi Matsche) (Kenyon and Rice, 1959), while temperate zone seals are often colonized by Enteromorpha, Xenococcus and Dermocarpa (Barnes and Powell, 1950). Enteromorpha groenlandica (J. Ag.) Setchell and Gardner often grows to 23 cm long on the guard hairs of the gray seal (Barnes and Powell, 1950). Colonized hairs are undoubtedly lost in various widespread locations as the seals migrate and thus probably dispersing the algae into new locations.

Cetaceans or whales also have a flora and fauna growing on their skin and teeth. Diatoms are the predominant algae living on whales (Amemiya, 1916; Bennett, 1920), especially Cocconeis (Hustedt, 1952) and Gomphonema (Hart, 1935; Kalcher, 1940; Nemoto, 1956; 1962) which have been taken from seven species of cetaceans captured in the Bering Sea. Navicula (Nemoto, 1956) and Stauroneis (Omura, 1950) may cause inflamation of the skin of whales, and other algae may be present (Penin, 1969; Pilleri, 1969; Payne, 1976) as colonizers on many of the barnacles that infest whales.

Turtles also have the potential to carry algae and sessile marine invertebrates across barriers. Various marine organisms are carried overland on the backs of terrapins (Jackson, et al., 1973; Ross and Johnson, 1972; Jackson and Ross, 1971) while Polysiphonia tsudana Hollenberg (Tsuda, 1965; Hollenberg, 1968) and Cladophora densa Collins (Kitami, 1972) have been found on sea turtles.

Parrot and puffer fishes, may also be colonized by various algae. Tsuda, Larson and Lujan (1972) have described the algal flora living on the beaks of parrot fishes in Micronesia. They found thirteen species of algae growing on three genera of parrot fish and one genus of puffer fish. These algae included species from the Chlorophyta, Phaeophyta, Rhodophyta, Cyanophyta and Chrysophyta. All were growing on the teeth of the fishes and a single parrot fish had up to five different species of algae on its beak.

Migratory shrimps may also be active in the dispersal of algae and sessile marine invertebrates. At times, the shrimp *Penaeus setiferus* may be found (Dawson, 1957) with *Balanus amphitrite niveus* Darwin growing on it. This is also true for the brown shrimp, *Penaeus aztecus* Pérez (Hildebrand, 1954) and the rock shrimp (Eldred, 1962). Shrimps such as these grow larger than 7 cm long and are probably effective transporters of algae.

Almost any swimming sea animal is a potential substraum for algae and invertebrates, and among the smaller fouled sea travelers are the marine snakes. Kitami (1968) found *Hydrophilus cyanocinctus* Gray near Sado, Japan, with the barnacle *Platylepas krügeri* Pilsbry growing on it. *Platylepas krügeri* was rare to Japan, and Kitami suggested that perhaps a closer look at other sea snakes may reveal various herpeticolous algae as well. This was done (Dunson, 1975) and not only barnacles (Zahl, 1975), but also *Navicula*, *Enteromorpha*, *Ulva*, *Giffordia mitchellae* (Harv.) Ham., *Spyridia filamentosa* (Wulfen) Harv. and *Cladophora* (Zahl, et al., 1975) were found on several species of sea snakes.

Summary

1. Rare meteorological phenomena, birds, insects, seals, whales, turtles, fish, shrimp and snakes can act as agents that could carry algae and other organisms across geographical barriers.
2. Algae carried by the means reviewed are generally the smaller, nearly microscopic forms.

Hypotheses

1. If migratory marine animals are thoroughly inspected, they will be found to have algae growing on their bodies that are normally found in shallow waters, near land masses far from the places the animals are captured.
2. The rate at which marine algae are entering the Hawaiian Islands by means of migratory animals is most likely higher than which could be accounted for by flotation alone.

<u>Dispersal of Algae Through Shipping Canals</u>

The most effective activity of man in overcoming land barriers to shipping has been the construction of canals such as the Suez, Panama and Volga-Don. The effect of these three canals on the dispersal of marine organisms has been significant and is considered in this section.

During the late Pliocene the land north of the Gulf of Suez rose and closed communication between the