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Erasure of Sediment Surface Features by *Mellita quinquiesperforata* (Leske)

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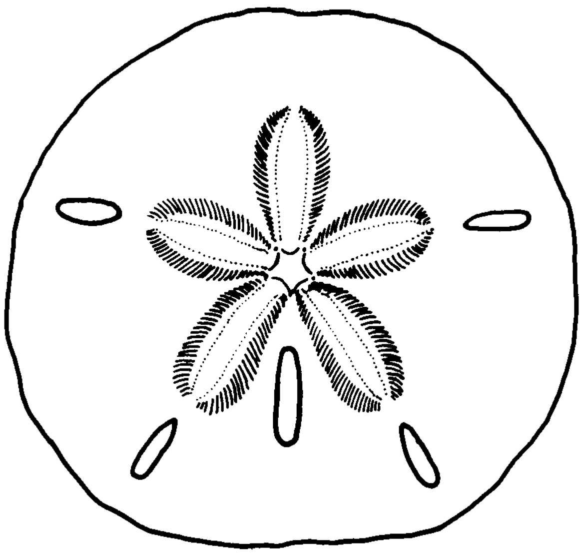

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by

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ABSTRACT

Erasure of sediment surface features by individuals of the species, *Mellita quinquiesperforata*, observed in this study suggests that all members of the sub-order, Scutellina, are able to erase sediment surface features. Sweep time, the time needed to erase the surface features of an area, depends on the population density, individual size, and speed of movement of the sand dollars. Assuming their pattern of movement as random, the following equation can be used to determine sand dollar sweep time,

$$T = 3.2 N^{-0.76} (W / S) (A / W^2)^{1.21}$$

where T is sweep time, N is the number of sand dollars, W is the average sand dollar width, S is their average speed, and A is the area under consideration. Known since the Eocene epoch, individuals of Scutellina may have erased sediment surface features in the past, thus giving reason for some sandstones being devoid of such features.

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INTRODUCTION

The benthonic population of the ocean floor includes a great variety of crawling and burrowing organisms, one member of which is the sand dollar, *Mellita quinquiesperforata* (Leske). Not only is this sand dollar a prominent member of the benthonic community, but also its feeding and burrowing mechanisms substantually modify the substrate in which it lives; its activities thus have considerable paleontological, paleoecological, and sedimentological significance (Bell and Frey, 1969). The study presented in this paper deals with the erasure of sediment surface features by *M. quinquiesperforata*.

Phylogeny and Occurrence

Phylogeny of *Mellita quinquiesperforata*

Mellita quinquiesperforata, known as the key-hole sand dollar, is a species of Echinodermata, a solely marine phylum characterized by pentamerous radial symmetry, calcareous spicules, and an ambulacral or water vascular system. By lacking arms or rays as do the starfish but by having a spiny firm body wall or test unlike the sea-cucumbers, *M. quinquiesperforata* is a member of the class Echinoidea. Bilateral symmetry imposed upon the pentamerous symmetry characterizes the order Clypeasteroidea of which *M. quinquiesperforata* is a member. The flattened forms of Clypeasteroidea are of the sub-order Scutellina, as is *M. quinquiesperforata*. Therefore, the common name sand dollar refers to the members of the sub-order Scutellina. Of the various families of Scutellina, the family Mellitidae is composed of those sand dollars that have perforations or lunules within the test. Those with five or six lunules are of the genus Mellita. *M. quinquiesperforata* differs from the other five-lunuled species of Mellita by having a more or less circular or pentagonal test, an apex more or less central, a periproct usually markedly longer than wide, and an unpaired lunule being about twenty percent of the test length (Caso, 1946; Clark, 1940; Cooke, 1959).

Geographic occurrence of *Mellita quinquiesperforata*

M. quinquiesperforata occurs upon the sands of the American Atlantic continental shelf from Nantucket, Massachusetts, United States of America in the north to Santos, Brazil in the south. The species is abundant along the Carolina and Florida coasts (Bell and Frey, 1969; Hyman, 1958; Moore, 1956; Salsman and Tolbert, 1965; Weihe and Gray, 1968). According to Caso (1946) none are found around the Bermuda Islands, but Mayr (1954) says they occur there. None have been reported from the Bahamas (Caso, 1946). They exist around the Greater Antilles and Trinidad but do not occur around the Lesser Antilles (Caso, 1946). M. quinquiesperforata occurs along the northern coasts (Parker, 1956) and western coasts (Caso, 1946; Ladd, Hedgpeth, and Post, 1957; Parker, 1959) of the Gulf of Mexico. Caso (1946) reports them found along the east coast of Central America and along the northeast coast of South America up from Brazil.

The extensive geographic domain of M. quinquiesperforata indicates the adaptability of the species to a large temperature range. Winter water temperatures of Nantucket may go down to 32° F and the waters of the Gulf of Mexico and the Caribbean Sea may get as hot as 86° F (H. O. Pub. No. 700). M. quinquiesperforata therefore is an eurythermal species.

As is the case with most echinoderms, M. quinquies perforata tolerates little change of salinity. Although it is generally found in areas having salinities of about 35°/oo, its habitat may extend into estuaries having lower salinities (Moore, 1966). After a large rain storm, Bell and Frey (1969) have seen M. quinquiesperforata with no apparent ill effects living in water having a salinity of 18 $^{o}/oo$. M. quinquiesperforata therefore is a stenohaline species that can be subjected to low salinities for short periods of time.

M. quinquiesperforata, a benthic species living within the shallow part of the littoral province, has been reported to a depth of approximately fifty meters (Weihe and Gray, 1968). In the Gulf of Mexico, the domain of M. quinquiesperforata ends at about ten to fifteen meters where the domain of Encope michelini begins (Moore, 1956; Salsman and Tolbert, 1965).

Substrate seems to be the primary physical ecological factor determining the location of M. quinquiesperforata within its geographic limits. Populations exist in habitats with firm quartz sand bottoms possibly containing shell fragments and consisting neither of an extremely coarse nor a silty texture (Bell and Frey, 1969; Parker, 1956; Salsman and Tolbert, 1965; Weihe and Gray, 1968). At Beaufort, North Carolina, Weihe and Gray (1968) found M. quinquiesperforata on sand with the most abundant grain size from 0.417 to 0.175 mm. From laboratory experiments involving artificial substrates, Bell and Frey (1969) observed that M. quinquiesperforata is either unwilling or unable to move when placed upon coarse gravel, can move about on fine gravel but cannot burrow into it, and dislikes mud. They conclude that the distribution of *M. quinquiesperforata* is apparently explained by the organism's ability to burrow into a given substrate which is related chiefly to particle size.

Stratigraphic occurrence of *Mellita quinquiesperforata*

Different species of the genus *Mellita* have existed since the Miocene epoch (Durham, 1966; Durham and Melville, 1957; Grant, 1933). Fossil *M. quinquiesperforata* have been found in the Pleistocene Cape May Formation of New Jersey (Richards, 1944), in the Pleistocene Pamlico Formation of Georgia (Cooke, 1942), and in the Pleistocene sediments of South Carolina (Cooke, 1959). The present writer has identified fragments of *M. quinquiesperforata* found in the Pleistocene sediments of Virginia. Therefore, *M. quinquiesperforata* occurs in various Pleistocene formations of some Atlantic coastal states of the United States.

Occurrence of other Scutellina

Species of the eleven genera of the sub-order are distributed throughout the world. Other than the genus *Mellita*, the genera *Echinarachnius* (Agassiz, 1872-1874;

Clark, 1914; Cooke, 1942, 1959; Durham, 1957, 1966; Ekman, 1953; Hyman, 1955; James and Stanley, 1968; Mortensen, 1948; Parker, 1927; Parker and Van Alystyne, 1932) and Encope (Agassiz, 1872-1874; Caso, 1961; Clark, 1914; Cooke, 1947, 1959; Hyman, 1955; Mayr, 1953; Moore, 1956; Mortensen, 1948; Salsman and Tolbert, 1965) live off the western or American coast of the Atlantic Ocean. The genera Dendraster (Chia, 1969; Clark, 1914; Durham, 1966; Hyman, 1955; McCauley and Carey, 1967; Mortensen, 1948; Raup, 1958), Echinarachnius (Cooke, 1942, 1959; Durham, 1957, 1966; Ekman, 1953; Hyman, 1955; Mortensen, 1948; Reese, 1966), Encope (Agassiz, 1872-1874; Clark, 1914; Durham, 1966; Hyman, 1955; Mayr, 1953; Mortensen, 1948), and Mellita (Agassiz, 1872-1874; Caso, 1946, 1961; Clark, 1914; Ekman, 1953; Mayr, 1953; Mortensen, 1948) occur off the eastern or American coast of the Pacific Ocean. In the seas around Japan live the genera Astriclypeus (Agassiz, 1872-1874; Clark, 1914; Durham, 1966; Ikeda, 1941; Mortensen, 1948), Echinarachnius (Agassiz, 1872-1974; Clark, 1914; Cooke, 1959; Mortensen, 1948; Reese, 1966; Zenkevitch, 1963), and Scaphechinus (Durham, 1966; Hyman, 1955; Mortensen, 1948). The genus Echinodiscus lives in the Indo-Malay region, the Red Sea, and off the east coast of Africa (Agassiz, 1872-1874; Clark, 1914; Durham, 1966; Hyman, 1955; Mortensen, 1948). Off the west coast of Africa lives the genus *Rotula* (Agassiz, 1872-1874; Clark, 1914; Durham, 1966; Ekman, 1953; Hyman, 1955; Mortensen, 1948). No species of Scutellina are reported to exist in the waters around England (Nichols, 1962) and other parts of Europe.

Ecological conditions of the Scutellina world distribution are similiar to the conditions in which *M. quinquiesperforata* lives. Temperatures range from 32^{o} F to 82.5^{o} F; salinity remains around 35^{o}/oo (H. O. Pub. No. 225). Although most Scutellina are littoral, some live at greater depths. Chia (1967) reports *Dendraster excentricus* at 200 meters. Mortensen (1948) reports *Echinarachnius parma* at 1625 meters. With regard to sediment, *Astriclypeus* sp. (Ikeda, 1941), *Dendraster excentricus* (Chia, 1969; McCauley and Carey, 1967; Raup, 1958), *Echinarachnius parma* (James and Stanley, 1968; Zenkevitch, 1963), *Encope michellini* (Salsman and Tolbert, 1965), *Mellita lata* (Kent, 1944), and *Mellita sexiesperforata*[1.2] (Goodbody, 1960) live on

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[1]synonyms: *Leodia sexiesperforata*, *Mellita sesquiperforata*, *Mellita sexies-perforata*, *Mellita sesies perforata*.

[2]Cerame - Vivas and Gray (1964) suggest that *M. sexiesperforata* is not a separate species from *M. quinquiesperforata*.

fine to coarse sandy bottoms, Crozier (1919, 1920) reports Mellita sexiesperforata on sediments ranging from shell sand to dark brownish mud. Cooke (1957) reports that the extinct genus Periarchus lived on both sand and calcareous ooze. Therefore, although there are exceptions, Scutellina occur primarily on the shallow part of the sandy continental shelves throughout most of the world.

Although only five Scutellina families exist today, eleven families have existed at some time since the Eocene (Durham, 1966; Durham and Melville, 1957). During the Miocene twenty-four Scutellina genera existed compared to the eleven genera for the present (Durham, 1966). If the number of genera indicates the abundance of individuals, the number of sand dollars was greater during the various geological periods of the past than there is today.

Examples of epochs, formations and areas for some fossil Scutellina are as follows:

Albertella aberti[3] from Miocene, Calvert and Choptank Formations in Maryland (Clark, 1915; Cooke, 1959; Schoonover, 1941; Warfield, Atkinson, Remson and Silvester, 1904), and the Chipola formation in Florida (Cooke, 1959);

Albertella palmeri from the Upper Caribe Formation in Guatemala (Durham, 1957);

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[3] synonym of Scutella aberti.

Astrodapsis sp. from Miocene, Pliocene, and Pleistocene in California (Eaton, Grant, Allen, 1941; Grant and Hertlein, 1938);

Dendraster sp. from Miocene, Pliocene, and Pleistocene in California and Alaska (Grant and Hertlein, 1938); Woodring and Bramlette, 1950);

Echinarachnius sp. from Miocene to Recent in Japan (Grant and Hertlein, 1938) and from Pliocene to Recent in Mexico, California, British Columbia, Alaska (Durham, 1957; Grant and Hertlein, 1938);

Encope sp. from Pliocene and Pleistocene in Galapagos, Chile, Ecuador, Mexico and California (Grant and Hertlein, 1938), from Miocene in South Carolina and from Pliocene in Florida (Clark and Twinchell, 1915);

Mellita carolina[4] from Miocene, Duplin marl in South Carolina and Yorktown Formation in North Carolina and Virginia (Clark and Twinchell, 1915; Cooke, 1959);

Mellita sexiesperforata from Bermuda sandstones (Moore and Moore, 1946);

Periarchus sp. from Eocene, Gosport sand and Ocala limestones in southern United States (Cooke, 1957 and 1959);

Protoscutella mississippieansis from Eocene, Winona sands in Mississippi, Mount Selman Formation in Texas, and Lisbon and Tallahatta formation in Alabama (Cooke, 1959);

Scutella leognanensis from Eocene to Miocene of Europe and North America (Mortensen, 1948).

Locations of the forementioned fossil and living sand

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[4]synonym of Leodia caroliniana.

dollars exemplify the stratigraphic and geographic ranges of the Scutellina. As seen, most Scutellina are recorded from those world areas that are or were sandy continental shelves.

Measurements and Movement of *Mellita quinquiesperforata*

The time needed for *M. quinquiesperforata* to erase sediment surface features of an area, herein referred to as sweep time, depends on three parameters: population density, individual size (width), and movement.

Population density

In areas where *M. quinquiesperforata* lives, Moore (1956) states that it appears to be not only the dominant organism but also the only one present. Average measured population densities range from 2 to 5 individuals per square meter (Bell and Frey, 1969; Weihe and Gray, 1968). Salsman and Tolbert (1965) report higher averages and give a maximum density of eight hundred and twenty-one individuals per square meter. Moore (1956) describes *M. quinquiesperforata* as being sometimes so crowded that they overlapped.

Individual size (width)

Width is the size measurement of *M. quinquiesperforata* that the erasure of sediment surface features depends upon. Caso (1946) and Salsman and Tolbert (1965) report average widths ranging from 40 to 60 mm. Weihe and Gray (1969) report that the greatest number of individuals had widths between 80 and 100 mm. They also report the largest *M. quinquiesperforata* at 130 mm. Weihe and Gray (1968) note the conspicuous absence of small individuals and neither they nor Salsman and Tolbert (1965) report any smaller than 12 mm. Therefore, according to the literature, the width of *M. quinquiesperforata* may range from 12 to 130 mm or ½ to 5 inches.

Movement

At first glance, *M. quinquiesperforata* gives the impression of inactivity because it moves slowly and has no clearly visible means of locomotion. On closer inspection however, thousands of small spines can be seen moving the sand dollar along at a slow rate. Some studies and descriptions of the locomotion of *M. quinquiesperforata* have been made (Bell and Frey, 1969; Hyman, 1958; Moore, 1966; Reese, 1966; Salsman and Tolbert, 1965; Weihe and Gray, 1968). Other than noting that M. quinquiesperforata normally lies upon or just beneath the sand surface and paralled to it, the rate and pattern of movement are all that need be considered here.

As previously stated, M. quinquiesperforata appears to be inactive because of its slow rate of movement. Rates have been measured both in the field (Bell and Frey, 1969; Salsman and Tolbert, 1965; Weihe and Gray, 1968) and in the laboratory (Weihe and Gray, 1968). Speeds range up to a maximum of 9.5 cm per 2 minutes (1.7 inch per minute) as recorded by Weihe and Gray (1968). No correlation seems to exist between speed and size of the individual (Bell and Frey, 1969; Weihe and Gray, 1968). Therefore, regardless of size, M. quinquiesperforata may move up to almost 5mm (2 inches) per minute, although the rate is generally much slower.

Continuous observation of many M. quinquiesperforata for extended periods of time is needed to determine whether or not their path of movement follows a pattern. No reports were found of such observations although Salsman and Tolbert may have such data. Weihe and Gray (1968) state that their studies indicate that the movement of M. quinquiesperforata is random. Their evidence based on the observation of the movement of 48 sand dollars on sand is that the average distance between the start and end points after 24 hours was only 0.72 inches greater than the average distance for 12 hours. Similiar results were obtained on a muddy bottom. Therefore, the movement of *M. quinquiesperforata* may be considered random unless proven otherwise.

FIELD METHODS

All measurements, photographs, and other observations were made in the study area in the shallow waters north of Fisherman Island (Fig. 1). On September 5, 12, and 24, 1969, areas of one-hundred square feet were staked out, located, and observed for individuals of M. quinquiesperforata. On the chart (Fig. 1), the locations of these three studies are indicated by their respective day numbers.

Measurements and Movement of Mellita quinquiesperforata

Density, orientation, width

Population density measurements of M. quinquiesperforata were made on the three days by counting the number of live individuals within the area of one-hundred square feet. Before the areas were staked out, a preliminary search of the general area was made to insure the presence of M. quinquiesperforata. Staking the area consisted of driving into the sediment, except for the last few inches, four, two foot long, three-eighths inch diameter, steel rods. Connected with crab line, the rods indicated the corners of a square having ten foot sides. No attempt was made to have areas of specific location or orientation. Once the area was marked off, horizontal sextant angles were recorded for charted points including the towers on Fisherman Island. These angles were taken from a standing position, either in the center of the staked area or in a boat positioned over the area. After getting fixes on the area, it was searched for sand dollars. Scuba equipment was used to facilitate the search. Sand dollars on the sand surface were located first. Before removing and placing them in a net bag, their axial orientations relative to magnetic north was noted. Angles were measured clockwise from magnetic north. Different compasses happened to be used each day, therefore different angle class intervals were recorded. After the sediment surface was clear of _M_. _quinquiesperforata_, the area was scoured to a depth of about two inches with fingers. Care was taken not to disturb the orientation of the animal. When one was located under the sand, the sediment was carefully swept aside so that orientation could be noted. If the orientation was considerably altered during the process, no measurement was recorded for that specimen. After the area was completely searched, the corner rods were removed. The _M_. _quinquiesperforata_ collected from the area were then counted and measured for width. Width, the largest distance across the test perpendicular to the central axis, was measured to the nearest one-eighth inch with a small rule or steel tape measure. Population density, orientation, and size were recorded for only the *M. quinquiesperforata* of the three staked areas.

Speed

Measurements of speed were made of some *M. quinquiesperforata* among the preceding three samples, and of other individuals as well. A shell, stick, or diver's knife was placed in the sand at the posterior end of the sand dollar. After a period of time, the distance traveled was measured with small rule to the nearest one-eighth inch. Time was measured with a sweep second hand of a diving watch.

Paths

Paths of travel or trails of four *M. quinquiesperforata* were observed for approximately one hour. At the start, a large finishing nail painted international orange was placed at the posterior of the sand dollar. At intermittent periods of elapsed time, measured with a diving watch, other nails were placed at the posterior of the sand dollar, disturbing it as little as possible. The pattern of movement was sketched and the distances between the nails were measured with a small rule to the nearest one-eighth inch. When three sand dollars were watched during the same period of time, the observations were made by two observers.

Photographs of *Mellita quinquiesperforata*

Photographing *M. quinquiesperforata* in the act of erasing sediment surface features proved to be a problem due to the turbidity of the water. Use of a 35 mm under-water camera was unsuccessful, despite trials of various speeds of black and white film, various combinations of f/stops and shutter speeds, with and without flash. The use of a view box solved the problem. A steel can, approximately 18 inches long and one foot in diameter, was made into a view box by replacing the bottom with clear plexiglass. Three steel rods, the same as those used for staking, were attached equally spaced around the sides of the can to stand and position it in the sand. The inside of the can was painted flat black and a wooden lid was made through which a two inch diameter hole was drilled to mount the camera. In the field, the view box was held down within a few inches off the bottom by strapping diving weights around the base of the view box. If a sand dollar was not in the field of view initially, one was placed there. Results were obtained with both Kodak Plus-X and Kodachrome films without the use of flash. Various f/stops and shutter speeds were used depending on the natural lighting conditions.

Measurements of the Environment

Water depth and salinity

Depth was noted on a few occasions, although not accurately measured. Water samples were taken in citrate bottles and later analyzed for salinity with a Hytech Model 6220 laboratory salinometer.

Grain size

During an extremely low tide, two adjacent but rather distinctly differing areas of sediment were noticed. One area contained sand dollars, but the other area had none. From these two areas, samples were taken from the upper one-half inch of bottom sediment using a small trowel. In the laboratory, the samples were analyzed for grain size. After being dried in an oven at approximately 100°C for about a day, the samples were split down to about fifty grams each. The samples were weighed on a Mettler Macro

Balance, wet sieved through a sixty-three micron screen, then dried once again at about 100° C for one day. After being weighed again to determine the amount of silt and clay, the samples were then sieved by means of a motor driven shaker through a $\sqrt[4]{2}$ series of standard woven wire screens for approximately a half hour. The sand resting upon each screen was weighed.

FIELD RESULTS

Measurements and Movement of Mellita quinquiesperforata

Density

Population densities of *M. quinquiesperforata* on September 5, 12, and 24 were respectively 36, 20, and 104 individuals per one-hundred square feet. Therefore, the density of *M. quinquiesperforata* ranged from 0.2 to just over 1 individual per square foot for the sample area.

Orientation

Orientations of *M. quinquierperforata* it was believed would give some indication as to the pattern of sand dollar movement. The results of the orientation observations are presented in Table 1. The data of each sample was tested with a Rayleigh test (Curray, 1956; Potter and Pettijohn, 1963) to see if the sand dollars had an orientation that could be attributed to something other than randomness. The results indicated that there was a greater than 5% probability of obtaining more sand dollars facing in the observed biased directions by chance alone; an absence of biased orientation is not accepted as significant unless there is less than a 5% probability of its occurring by chance. Therefore, there is no evidence that the M. quinquiesperforata sampled were not randomly oriented.

Size

Width measurements of the three M. quinquiesperforata samples are presented as a combined frequency distribution in Figure 2. Class increments of width are in eighths of an inch, as were the measurements. The frequency distribution of the three combined samples was tested for goodness of fit to a normal curve with a chi-square test. With a confidence interval of 95%, the test shows that the frequency distribution of the width measurements fit a normal curve distribution. Average size and standard deviations of the three samples are presented in Table 2.

Speeds

The various speeds of four different sand dollars are presented in Table 3. The dashes shown in this table indicate that no trial was made. As can be seen, the rates neither on, nor under, the sediment surface are dependent on size. These short trials indicate that M. quinquiesperforata can travel up to 1.5 inches per minute on the sediment surface and 0.5 inches per minute beneath the surface. The paths presented in Figures 3 and 4 show a maximum surface speed of 3 inches per minute and an overall average buried speed of almost 0.5 inches per minute.

Paths

Scale drawings of the trails are presented in Figures 3 and 4. The circles represent the nails used to mark the trails. The numbers within the circles represent elapsed time. The three trails formed during the same period of time indicate no inner-related direction or pattern of movement. Though limited in time and number, these paths indicate neither a distinctive nor simple pattern of movement for *M. quinquiesperforata*.

Photographs

Two series of three photographs each are presented in Figures 5 and 6. In both series, the position of the view box remained fixed as the sand dollar moved across the field of view erasing sand ripples. Each photograph in the series was taken about five minutes apart; A1 and B1 at the start, A2 and B2 next, and A3 and B3 still later. The A series shows ripple erasure when the sand dollar moves on the sediment surface. The B series shows erasure when the sand dollar moves beneath the sand surface. In both series, one pass by the sand dollar levels the sediment surface features.

Measurements of the Environment

Water depth and salinity

Depths of the study area ranged from zero at low tide to approximately four feet at other times. Salinity of the area ranged from 31.6 to 32.1 $^{0}/oo$ during the period of observation.

Grain size

Grain size analysis results are presented as histograms in Figure 7. Histogram A represents sediment that is characteristic of the area devoid of *M. quinquiesperforata*; histogram B represents the sediment of the area in which the sand dollars were found. The histograms do not show the strong difference in grain size of the two areas that appeared to exist in the field. A veneer of fines on the area of sample A and not on the area of sample B may have existed thus giving cause for the visual difference being greater than that indicated by the histograms.

RANDOM WALK THEORY

Use of the mathematical concept of random walk arises when one is confronted with probabilistic subjects that range from simple gambling games to particle collisions of diffusing gases. Although a random walk game may be played with movement unlimited in direction and amplitude, most games are restricted in movement by allowing only specific directions and/or amplitudes and by establishing boundaries around an area. With such limitations, the random walk game more closely resembles the subject presently being examined. How then can these limited movements be considered random? In the so-called symmetrical cases, equal probabilities are assigned to the allowable directions and/or amplitudes of movement.

Although the movement may be continuous, it can be broken down into increments called trials. Each trial may be either dependent or independent of other trials. When the outcome of any trial depends on the outcome of the directly preceding trial and only on it, the sequence of trials are termed a Markov chain (Feller, 1950). Therefore, in Markov chains, the probability of an outcome depends on both the probability of having an outcome provided the previous ontcome occurred, and the probability of having the previous outcome.

If an individual of M. quinquiesperforata has no distinct pattern of movement and therefore is assumed to have random movement as suggested by some observers, a theoretical sweep time can be calculated by creating a planar random walk game utilizing Markov chains.

Description of Rules

A random walk game has definite rules. These rules define the area to be played upon, state how to begin the game, describe the movement allowed, assign probabilities to those movements, and indicate when the game ends. Some of these rules for the game herein developed are illustrated in Figure 8.

Area

The random walk game herein developed is played in a square area. Four reflecting boundaries surround the area. The area is divided alternatively into 4, 9, 16, 25, 36, 49, 64, 81, or 100 smaller areas called blocks. There could be more blocks but the games were played with only those listed.

Initialization

At the onset of the game one of the blocks must be occupied. The probability of this block being initially occupied is unity (1) and the probability of first time entrance is also unity (1). These probabilities are considered to apply to move (trial) 0, and the outcome of this move is then certain. For the initial condition, all the rest of the blocks are assigned probabilities of entrance and first time entrance of 0; they are not occupied at the onset of the game. This assignment of the probabilities of 1 or 0 to the various blocks at the onset of the game is termed initialization.

Movement

After the area has been divided into blocks and they have been initialized, movement of a point (ie., a sand dollar) may begin. A move (trial) is defined as a passage from the initially occupied block into one of the adjacent blocks. Adjacent blocks are those blocks that share a common side with the occupied block. Movement is possible therefore in four directions only. The probability of moving in any one of the four directions is set equal to 0.25.

Movement from any of the peripheral blocks may be directed into a reflecting boundary. When this occurs, the outcome is that the block is not vacated. For example, if on attempting to leave a room, a man finds the door closed, he can not leave the room. Note that he is able to move in the direction of the doorway, but he does not leave the room when the door is closed. In the same way, a reflecting boundary does not allow passage from the block; retention of the point in the block is the outcome of that specific move (trial). Therefore, the definition of a move is modified to include movement stopped by a reflecting boundary which causes retention in the block.

Transitional probabilities

As stated before, movement has an equal chance of occurring in four directions; the probability of moving in any single direction being 0.25. When considering the probability of moving from one block to another, or remaining in the block, three different classes of blocks appear. Referring to Figure 8, there are corner blocks (1, 4, 7, 10), side blocks (2, 3, 5, 6, 8, 9, 11, 12), and inner blocks (13, 14, 15, 16). Movement into an adjacent block from any of the three classes of blocks is 0.25, but the probability of remaining in the block depends upon which class it belongs to. Movement from corner blocks encounter reflecting boundaries in two of the possible four directions; therefore, the probability of remaining in a corner block is 0.50. Movement from side blocks encounter reflecting boundaries in one direction; therefore, the probability of remaining in a side block is 0.25. Movement from inner blocks is always into an adjacent block, so there is no probability of remaining in the same inner block after a move. These probabilities of movement into another block or of retention in the same block are termed transitional probabilities. Therefore, a transitional probability is the probability of moving from one stated block to another stated block or remaining in the original block.

Termination of game

Because the purpose of this game is to determine how many moves are needed to cover the whole area, the game ends when the probability is high of having entered each and every block. The probability of 0.95 was chosen to terminate the games.

Description of Equations

The equations developed below indicate how many moves are needed to produce the joint probability of 0.95 of a point having entered each and every block.

Probability of entrance

The probability of being in a given block on a given move is symbolized by $p_k^{(n)}$, n representing the move and k representing the block. This probability depends on the probability of having the wanted outcome and[5] the probability of having a necessary previous outcome. The probability of having the wanted outcome is synonymous to the transitional probability. The probability of having a necessary previous outcome related to block k is the probability of occupying a block adjacent to block k. For example, referring to Figure 3, block 2 can be entered from block 1. Therefore, the probability of entering block 2 on a specific move is the probability of having entered block 1 on the previous move and[5] the probability of moving from block 1 to block 2. The equation for the probability of entrance into block 2 becomes:

$$p_2^{(n)} = p_1^{(n-1)} \; p_{1\,2}^{(1)}$$

The equation states that the probability of entering block 2 on some move, n, equals the probability of having entered block 1 on the previous move, times the probability

[5] the "and" condition means that the product of the probabilities is formed.

of moving from block 1 to block 2 in one move. But, block 1 is not the only block from which block 2 can be entered in one move. Block 2 can also be entered in one move from block 3, from block 13, and by returning from a reflecting boundary into itself. The probability of entering block 2 is therefore equal to the probability of being in block 1 previously and moving into block 2, or[6] the probability of being in block 3 previously and moving into block 2, or[6] the probability of being in block 2 and remaining there. Therefore, the probability of entering block 2 from all possible directions can be written as follows:

$$p_2^{(n)} = p_1^{(n-1)}\, p_{1\,2}^{(1)} + p_3^{(n-1)}\, p_{3\,2}^{(1)} + p_{13}^{(n-1)}\, p_{13\,2}^{(1)} + p_2^{(n-1)}\, p_{2\,2}^{(1)}$$

If v represents any of the blocks from which block 2, can be entered and k is substituted for 2, the above equation takes the general form:

$$(1) \qquad p_k^{(n)} = \sum_v p_v^{(n-1)}\, p_{v\,k}^{(1)}$$

The symbol $p_{v\,k}^{(1)}$ is simply the transitional probability from block v to block k. The symbol $p_v^{(n-1)}$ represents the proba-

[6]the "or" condition indicates a summation of the probabilities.

bility of entering block v on the move before move n. The only $p_v^{(n-1)}$ for which there has been presented a value is when (n-1) equals zero at the initialization of the game. When (n-1) equals zero, $p_v^{(n-1)}$ equals either unity or zero depending on whether or not block v was occupied at the onset of the game. When (n-1) is some value other than zero, $p_v^{(n-1)}$ can only be obtained through a process of substitutions of $p_v^{(n-1)}$ into the equation (1) as $p_k^{(n)}$ until (n-1) becomes zero. For example, referring to Figure 8 once again, the probability of entering block 2 on the second move is expressed as

$$p_2^{(2)} = \sum_v p_v^{(2-1)} \; p_{v\,2}^{(1)} = \sum_v p_v^{(1)} \; p_{v\,2}^{(1)} ,$$

expanded for all of the v's as

$$p_2^{(2)} = p_1^{(1)} \; p_{1\,2}^{(1)} + p_2^{(1)} \; p_{2\,2}^{(1)} + p_3^{(1)} \; p_{3\,2}^{(1)} + p_{13}^{(1)} \; p_{13\,2}^{(1)} .$$

Because there are no values for $p_1^{(1)}$, $p_2^{(1)}$, $p_3^{(1)}$, and $p_{13}^{(1)}$, each must be entered into equation (1) as $p_k^{(n)}$. This manipulation can be exemplified with $p_1^{(1)}$.

$$p_1^{(1)} = \sum_v p_v^{(1-1)} \; p_{v\,1}^{(1)} = \sum_v p_v^{(0)} \; p_{v\,1}^{(1)}$$

expanded for all of the v's as

$$p_1^{(1)} = p_1^{(0)} \; p_{1\,1}^{(1)} + p_2^{(0)} \; p_{2\,1}^{(1)} + p_{12}^{(0)} \; p_{12\,1}^{(1)} .$$

Probability of first time entrance

The next equation gives the probability of entering a block for the first time on a specific move. This probability is symbolized by $f_k^{(n)}$ where n represents the move and k represents the block. This means that the block is to be entered on the move in question but not on any of the preceding moves. The probability of first time entrance into a block as developed in this study is the probability of having entered the block on a move and[5] the probability of having not entered the block on any previous move. The probability of entrance into a block on a given move has been developed in the preceding section. The probability of having not entered the block on any of the previous moves now needs explanation. Because the probability of an event not happening is simply one minus the probability of it happening, the probability of having not entered the block for the first time on a specific move is one minus the probability of having entered it for the first time on the move in question. The probability of not having entered the block for the first time in a series of moves becomes one minus the probability of having entered it on one or[6] any other move. For example, the probability of first time entrance into block 2 on move 2 is equal to the probability of entrance into block 2 on move 2 and[5] one minus the probability of first time entrance into block 2 on move 1 or[6] the probability of first time entrance into block 2 at the onset of the game, move 0. The equation for this example is written:

$$f_2^{(2)} = p_2^{(2)} \left[1 - \left(f_2^{(1)} + f_2^{(0)}\right)\right] .$$

Allowing k to represent the block and n to represent the move in question, the equation takes the general form,

$$(2) \qquad f_k^{(n)} = p_k^{(n)} \left(1 - \sum_{r=0}^{(n-1)} f_k^{(r)}\right)$$

where r creates a range of n's starting from the onset of the game, move 0. The term $f_k^{(r)}$ is obtained by repeated substitution back into equation (2) until all r's are equal to zero, as was $p_v^{(n-1)}$ into equation (1) in the preceding section.

Joint probability of first time entrance

The probability of entering a block at least once during a series of moves can also be expressed in terms of the probability of first time entrance into the block on each of the various moves. For example, the probability of first time entrance during the first 2 moves depends upon the probability of first entrance on move 2 or[6] the probability of first time entrance on move 1 or[6] the probability of first time entrance at the onset of the game, move 0. Therefore, the probability of entering a block at least once up to and including the move in question, written $F_k^{(n)}$, is equal to the summation of the probabilities of the first time entrance of all of the moves. The equation is written:

$$(3) \qquad F_k^{(n)} = \sum_{n=0}^{n} f_k^{(n)} \quad .$$

The final equation, that for the probability of entering all of the blocks is a simple extension of the above equation. For example, the probability of having entered the sixteen blocks at least once during a series of moves depends on the probability of having entered block 1 during the series of moves and[5] the probability of having entered block 2 during the series of moves and[5] so on, up to and including the probability of having entered block 16 during the series of moves. Therefore, the probability of having entered all blocks is equal to the product of the probabilities of having at least entered each of the blocks once during the series of moves. The equation for this joint probability of having entered all of the blocks at least once may be written as follows:

$$(4) \quad F_B^{(n)} = \sum_{k=1}^{B} F_k^{(n)}$$

where B represents the totality of the blocks in the area. When $F_B^{(n)}$ reaches 0.95, the game is terminated.

APPLICATION OF RANDOM WALK THEORY

The preceding game and equations were programed for the IBM 1130 and IBM 360 computers using Fortran IV. The following is a discussion of the results of these programs. A sweep time equation is developed for M. quinquiesperforata using the foregoing results and population density, width, and speed of movement.

Single Starter

By assigning unity to only one block of the area at the onset of the game, the random walk games are played using only one starter. Placing the starter alternatively in various blocks gives the results that the least moves to end the game occur when the starter is in the center and the most moves needed to end the game occur when the starter is in a corner. Table 4 presents the results of playing random walk games starting in those two locations. The results of starting in both locations differ by no more than 5%. The number of moves for the corner starting positions are used for further development, therefore insuring at least a 95% probability of entering all blocks regardless of starting position.

Multiple Starters

In order to have more than one starter in the random walk game, more than one block is assigned unity at the onset of the game. Once again different numbers of moves are obtained to terminate the game when using the same number of starters but varying their initial positions. The dependency on packing and location in a sixteen block area is illustrated in Figure 9. More moves are needed to terminate the game when the starters are all packed initially into the corner blocks than when the starters are scattered over the area. The results of starting various numbers of starters packed in the corner blocks for areas of various numbers of blocks are presented in Table 5.

Derivation of Sweep Time Equation

The numbers of moves needed to terminate random walk games of one and more starters presented in Tables 4 and 5 are plotted logarithmically in Figure 10 as a function of the number of blocks. Parallel lines drawn through these points represent the same number of starters having moved within areas of various numbers of blocks. All the lines can be expressed by the equation,

$$(6) \quad M = C\,B^{1.21}$$

where M is the number of moves, B is the number of blocks, 1.21 is the slope of the lines, and C is a variable equal to the y intercept of each line. A logarithmic plot of these C's as a function of the number of starters or individuals is presented in Figure 11. These points lie approximately on a line whose equation is:

$$(7) \quad C = 3.2\,N^{-0.76}$$

where C is once again the value of the y intercept, N is the number of individuals, -0.76 is the slope of the line, and 3.2 is the x intercept of the line. The combination of equations (6) and (7) yields the equation,

$$(8) \quad M = 3.2\,N^{-0.76}\,B^{1.21}$$

With this equation the number of moves needed to enter all the blocks of an area with the joint probability of 95% is now a function of the number of starters and blocks of the area; assuming the movement to be random. Also, it should be recalled that the number of moves gotten from this equation represents the results of an initial packing of the starters into corner blocks. If the initial positions of the starters is anything other than in the corner blocks, a lesser number of moves than gotten by equation (8) is needed to have a joint probability of 95% to enter all the blocks of the area.

The number of moves, blocks, and starters must now be expressed in terms of the M. quinquiesperforata measurements of width, speed, and population density. Number of starters simply becomes the number of sand dollars in the area under consideration. The number of blocks is a function of both the area occupied by sand dollars and the width of the sand dollars. The area is divided into blocks with sides equal to the average width of the sand dollars. For instance, a one square foot area would be divided into thirty-six blocks when containing two inch sand dollars. The number of blocks can therefore be expressed by the equation,

$$(9) \quad B = A/W^2$$

where B is the number of blocks, A is the area, and W is the average width of the sand dollars. The number of moves is a function of time, speed, and width. For example, if a two inch sand dollar moves one-half inch per minute, in sixteen minutes it would travel a distance equivalent to four blocks. The number of moves can therefore be expressed with the equation,

$$(10) \quad M = ST/W$$

where M is the number of moves, S is the speed, T is the time, and W is the width. By substituting equations (9) and (10) into equation (8), the following equation is obtained,

$$(11) \quad ST/W = 3.2\ N^{-0.76}(A/W^2)^{1.21} \quad .$$

The equation for sweep time then becomes,

$$(12) \quad T = 3.2\ N^{-0.76}(W/S)(A/W^2)^{1.21} \quad .$$

Therefore, the time needed for M. quinquiesperforata to erase with the probability of 95% the sediment surface features of a certain area depends on the number of sand dollars, their average width, their speed, and the size of the area under consideration.

Evaluation of Sweep Time Equation for Different Conditions

The sweep time equation (12) can be used to determine the sweep time for any set of conditions. Area can range from a few square inches to many square miles; speed can range from nearly zero to a maximum of about two inches per minute; number can range from one to millions; width can range from about one-half inch to not much more than five inches for *M. quinquiesperforata*. By programing the sweep time equation for an IBM 1130 and having the results presented on a x-y plotter, the graphs of Figure 12 were made. As would be expected, sweep time decreases with an increase of width, speed, and number of sand dollars. It is interesting to note that if the speed, width, and population density remain constant, but the area and number of sand dollars increase, the sweep time also increases.

DISCUSSION

Photograph Interpretation

Two series of photographs presented in Figures 5 and 6 show that individuals of *M. quinquiesperforata* erase sediment surface features. The features in the photographs are sand ripples about one inch in height and three inches in wave length. The bulldozing or snowplowing of the ripples by a sand dollar moving on the sediment surface is shown in Figure 5. The same effect but by a sand dollar moving beneath the sediment surface is shown in Figure 6. Individuals of *M. quinquiesperforata* flatten out these and smaller features such as animal tracks in one pass, but features with more relief may take more than one pass to be erased by an average sized sand dollar.

Comparison of Observations

Erasure rate parameters

The parameters needed for determining the sweep time for individuals of *M. quinquiesperforata* in a specific area are their average speed, average width, and population density. Measurements of speed in this study are somewhat higher than those mentioned in the literature. Because *M. quinquiesperforata* is negatively phototaxic, the turbidity of the water in the study area may have enhanced their movement. All observations show that individuals of *M. quinquiesperforata* are capable of moving up to 3 inches per minute, but they generally move less than one inch per minute.

In this study, the observed range of sand dollars widths from 1.8 to 4.2 inches falls well within the range from 0.5 to 5.0 inches observed by other researchers. Width distribution of the combined three samples of this study reflect a normal distribution, as do two of Weihe and Gray's (1968) samples. And, because speed is not a function of size, the average width of such a population is a valid measurement to use in the sweep time equation. Measurements of population density of this study are lesser than those densities reported in the literature.

Area limitation

Sediment grain size appears to be the most important physical environmental factor determining where individuals of *M. quinquiesperforata* will be found within its geographic range. There appears to be both an upper and lower limit of grain size upon which the sand dollar will live. Other researchers have noted that individuals of _M_. _quinquiesperforata_ will not move on gravels. This was not observed in this study because no gravels or coarse sediments were present in the study area. But, a measurement of the lower limit of grain size that individuals of _M_. _quinquiesperforata_ will live upon was obtained. The mean lower grain size limit upon which the sand dollar lives is somewhere less than 2.38 Ø approaching 2.75 Ø. But if the earlier suggestion is correct that the fines of sample A area veneered the surface of that area, the lower grain size limit would be finer.

Paths

By following the paths or trails of _M_. _quinquiesperforata_, one could determine if their movement has a pattern or is random. The paths of four of these sand dollars presented in Figures 3 and 4 indicate no distinctive pattern, just straight line segments with irregular turns. The three paths observed during the same period of time in the same proximity show neither a relationship with each other nor the environment. If a relation exists between the movement of the sand dollar and some environmental condition such as current, the three sand dollars should have headed nearly in the same direction. They did not. Although this evidence indicates no relation in their paths and any environmental force or condition, the possibility may still exist that they move in patterns not related to environmental factors and not indicated within the period of time during which they were observed in this study. However, Weihe and Gray's (1968) observations do entail longer periods of time, 24 hours. The conclusion of their observations was that individuals of *M. quinquiesperforata* move randomly.

Sweep Time as Determined by the Equation

With the sweep time equation (12) and values for the three required variables, a sweep time for a given area can be obtained that is 95% probable, assuming random movement. A problem handling population density exists with use of this equation. Density, itself, never enters the equation, but its two components, number of individuals and size of area, do. As noted before, if speed, width, and population density are kept constant but both number and area are increased, the sweep time increases also. This increase of sweep time is seen in the different graphs of Figure 12 for the constant density of one sand dollar per square foot. The graphs to compare are one sand dollar per one square foot, twenty-five sand dollars per twenty-five square feet, one-hundred sand dollars per one hundred square feet, and 43,560 sand dollars per acre. Part of this increase of sweep time can be attributed to one of the assumptions of the random walk games that the starters are initially packed into the corner blocks. Because this packing does not account for all the increase in time, some care should be taken when choosing the size of the area entered into the sweep time equation. Some degree of freedom in choosing the area size exists because a 1,000 fold increase in area creates only a 10 fold increase in sweep time as can be seen in the graphs previously referred to.

Salsman and Tolbert (1965) gave an interesting problem that could be considered if more data were available. They observed a ripple bed erased by individuals of *M. quinquiesperforata* in approximately twelve hours. Given the speed, width, and population density of these sand dollars, the sweep time equation could be evaluated. A rather accurate measurement of the area size would also be needed. Because the ripples were rather large, six inches in height, whether or not the sand dollars needed one pass to erase the ripples would have to be known also.

Extension of Erasing of Features to All Scutellina

Members of the sub-order Scutellina, exemplified by *M. quinquiesperforata*, may erase sediment surface features because they all have a similiar way of life which consists in moving on or beneath the sediment surface. Although each Scutellina species is limited to a specific habitat, most of the continental shelves of the world are lived upon by some individual species of sand dollar. Sand dollars not only live on present marine sediments, but also have lived on marine sediments since the Eocene. Although only size can be measured for fossil sand dollars; the size, rate of movement, and population density of some living Scutellina species have been measured. These measurements of living sand dollars should be applicable to fossil sand dollars assuming the habits of the sand dollars have not changed in geologic time.

Most Scutellina species are about the same size as *M. quinquiesperforata*. *Echinodiscus auritus siamensisis*, one of the largest sand dollars, may measure up to about 180 mm or 7 inches (Mortensen, 1948). Movement of various

Scutellina species has been observed to be similiar to that of *M. quinquiesperforata* (Chia, 1969; Goodbody, 1960; Ikeda, 1941; Kenk, 1944; Parker and Van Alstyne, 1932; Reese, 1966). Population densities of various Scutellina species have been recorded being as large as those densities recorded for *M. quinquiesperforata*. Bradley (1957) reports *Echinarachnius parma* so abundant that they were touching; Zenkevitch (1963) presents a photograph showing an overlapping of these sand dollars. *Dendraster excentricus* may be found in densities up to 468 specimens per square yard (MacGinitie and MacGinitie, 1949). Because the measurements and the way of life of living Scutellina species are analogous to those of *M. quinquiesperforata*, it is concluded that individuals of extinct and living Scutellina species may erase sediment surface features in sweep times comparable to sweep times of *M. quinquiesperforata*.

Creation vs. Destruction of Features

Sand dollars do not live on a static sediment surface. Physical and/or biological agents continually or periodically mold and carve the sediment surface. In areas with continually active creative agents, sand dollars can only keep the area devoid of features when the population density is such that they almost overlap. In areas where features are periodically formed, such as esturaries where tidal currents may create features, fewer sand dollars are needed to destroy the features. Therefore, the sediment surface seen at any one time is the result of the rate of feature formation and the rate of feature destruction being in or out of balance.

In areas where the rate of feature formation exceeds the rate of feature destruction, sand dollars may do more permanent damage to the sub-surface sediment features than they do to the surface features. Epoxied box cores of sediments lived in by sand dollars and/or X-ray studies of artificially stratified sediments (Howard, 1968) may support this suggestion.

CONCLUSIONS

1. Individuals of *Mellita quinquiesperforata* are engaged in erasing sediment surface features in areas where they live on the American Atlantic continental shelves from Nantucket to Santos, Brazil.

2. Individuals of other Scutellina species are engaged in erasing sediment surface features in areas where they live on the continental shelves throughout most of the world.

3. Not only are sediment surface features being erased presently, but also sediment surface features of the past may have been erased by sand dollars. Past erasure of sediment surface features by sand dollars may have resulted in some sandstones dating back to the Eocene being devoid of features.

4. Assuming sand dollars have no simple and orderly pattern of movement, a theoretical sweep time can be calculated from a planar random walk game using an analysis theory based on the Markov process. This game results in the sweep time equation,

$$T = 3.2\ N^{-0.76} (W/S)\ (A/W^2)^{1.21}\ .$$

5. The sediment surface seen at any one time is the result of the rate of feature formation and the rate of feature destruction being in or out of balance.

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DEFINITIONS OF SYMBOLS

Symbols from random walk game

p - probability of entrance into a block

k - block entered

n - move of entrance

v - block(s) adjacent to block k

f - probability of first time entrance into a block

F_k - probability of entering a block in a series of moves

F_B - joint probability of entering all blocks

B - all blocks of an area

Symbols from sweep time equation and its derivation

M - moves needed for 0.95 probability of entrance

C - y-intercepts

B - all blocks of an area

N - number of starters or sand dollars

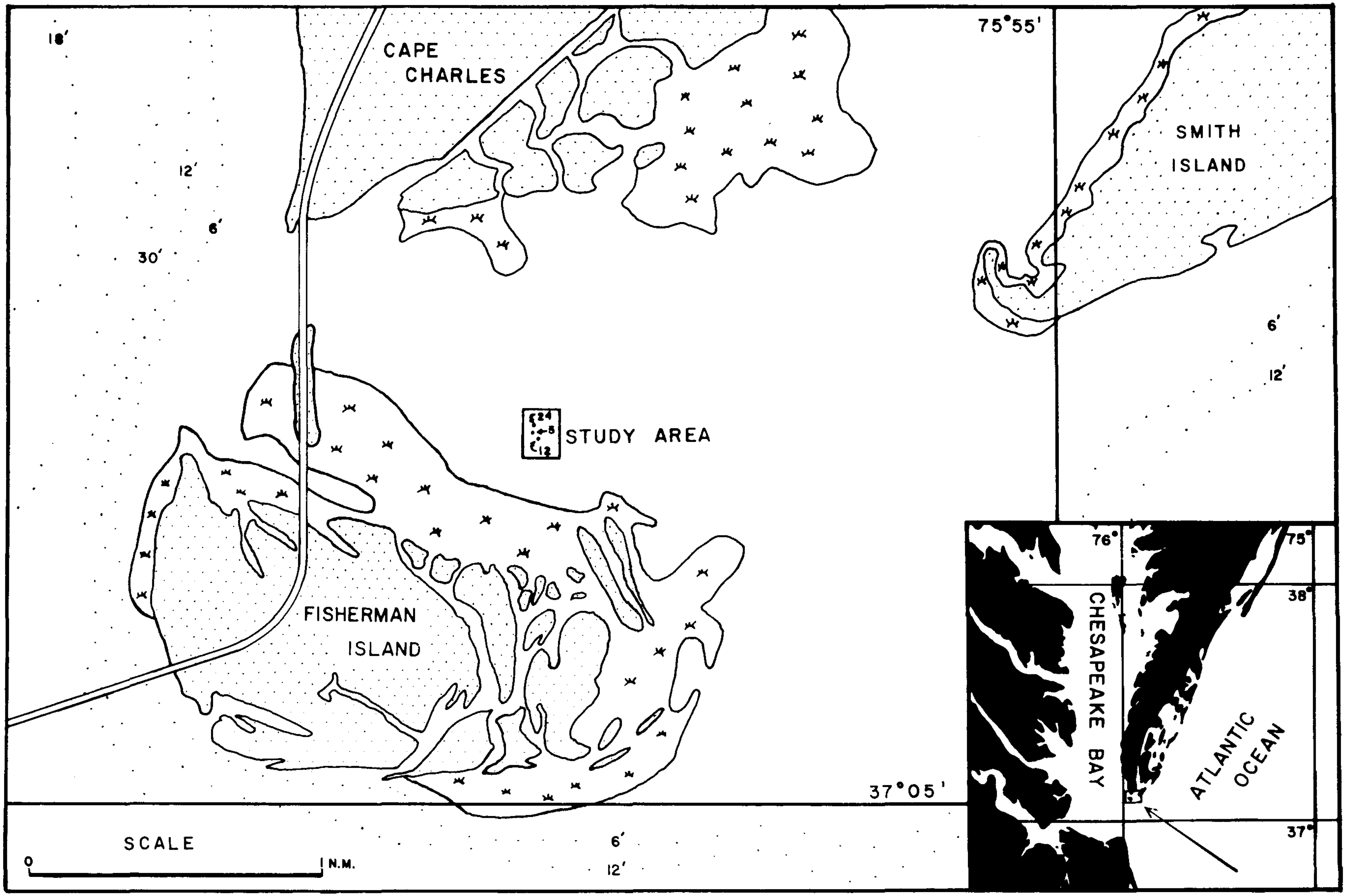
A - area

W - width of sand dollars

S - speed of sand dollars

T - sweep time

Figure 1. - Chart of Fisherman Island located on the eastern shore of the Chesapeake Bay. The boxed study area contains three dated locations of the primary samplings.


CAPE
CHARLES
SMITH
ISLAND
FISHERMAN
ISLAND
STUDY AREA
75°55'
37°05'
18'
12'
6'
30'
SCALE
0
1 N.M.
76°
75°
38°
37°
CHESAPEAKE BAY
ATLANTIC
OCEAN

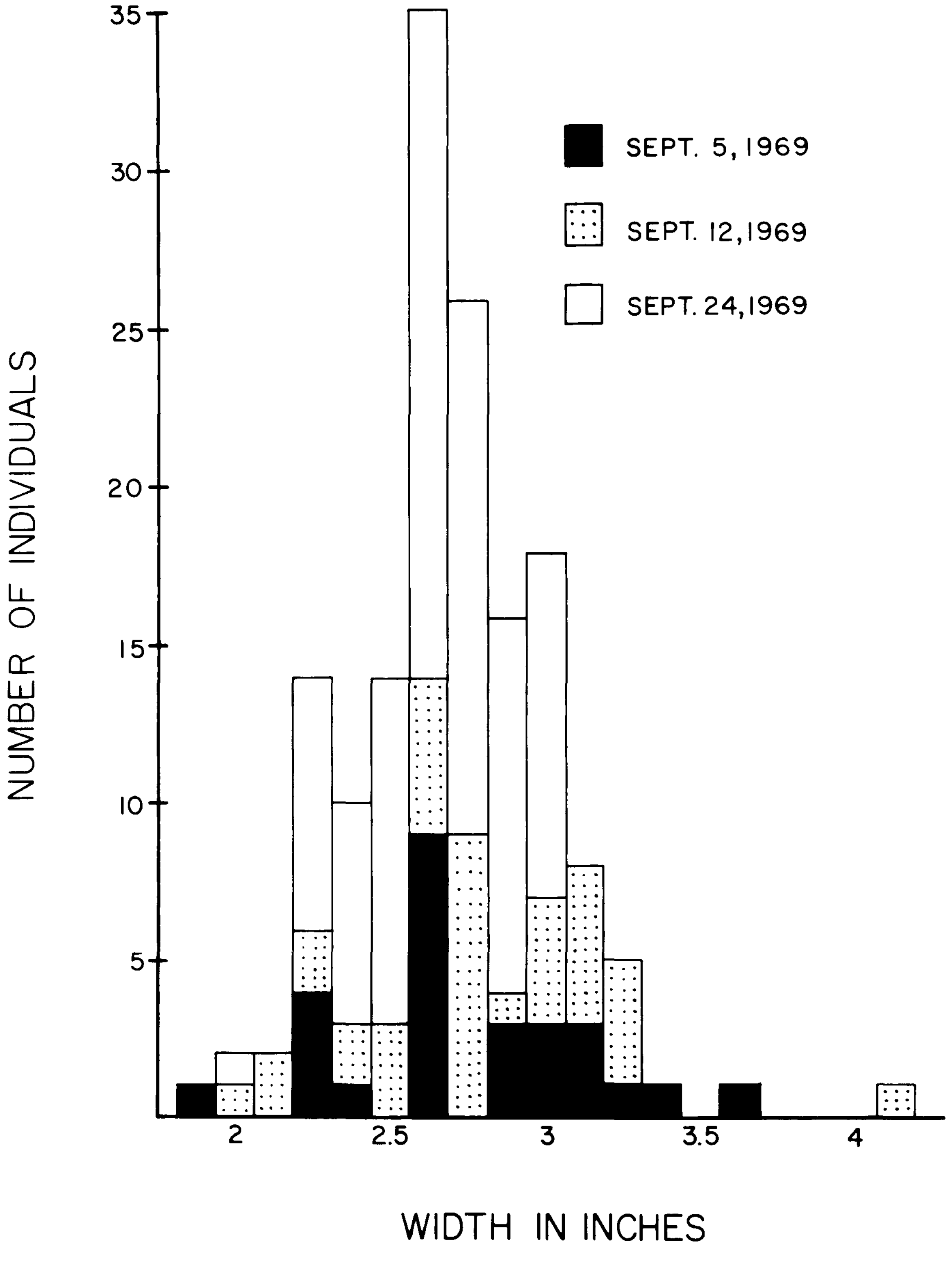


Figure 2.—Pooled width distribution of three samples taken north of Fisherman Island as in Figure 1.

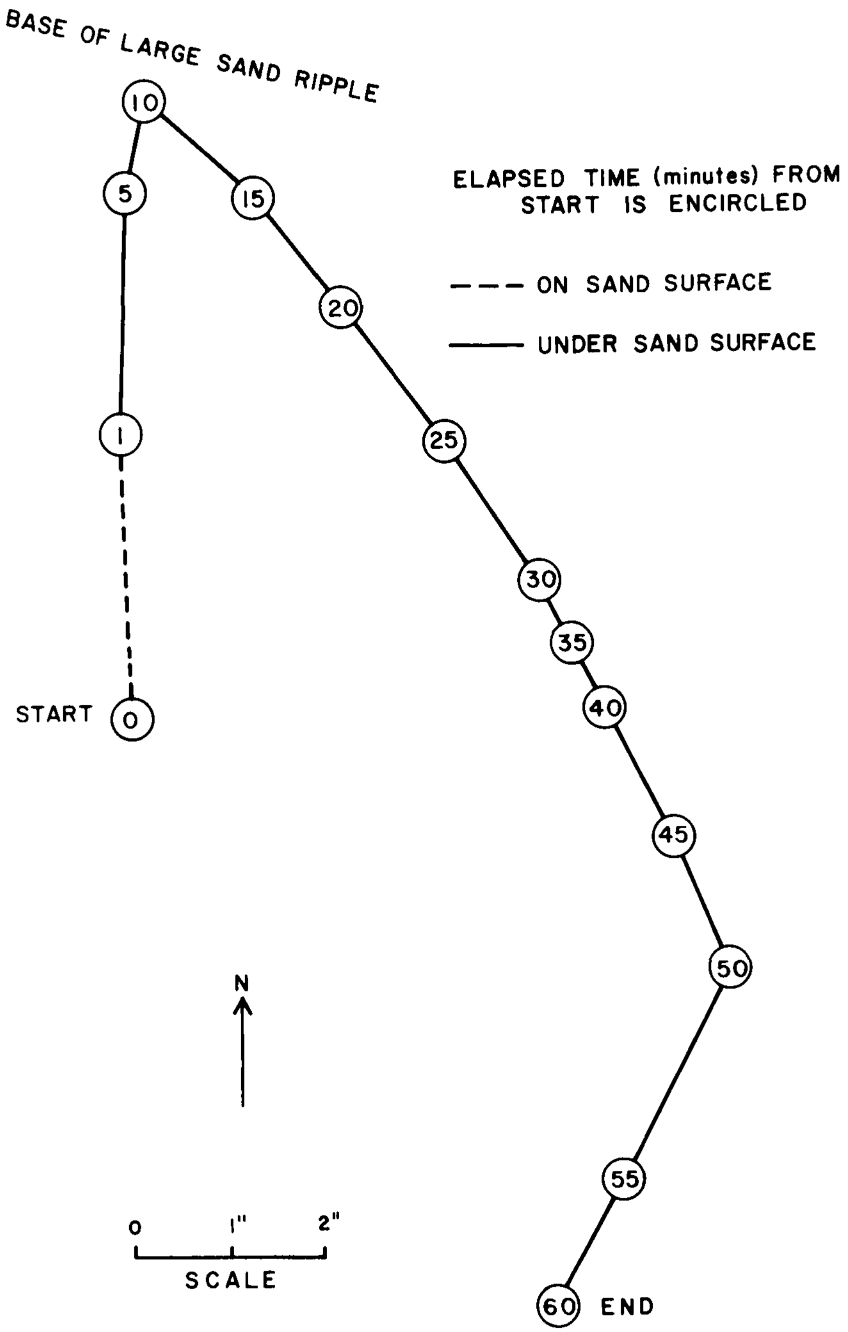


Figure 3.— Path of a sand dollar on Sept. 12, 1969 in about 3 feet of water in study area north of Fisherman Island, see Figure 1.

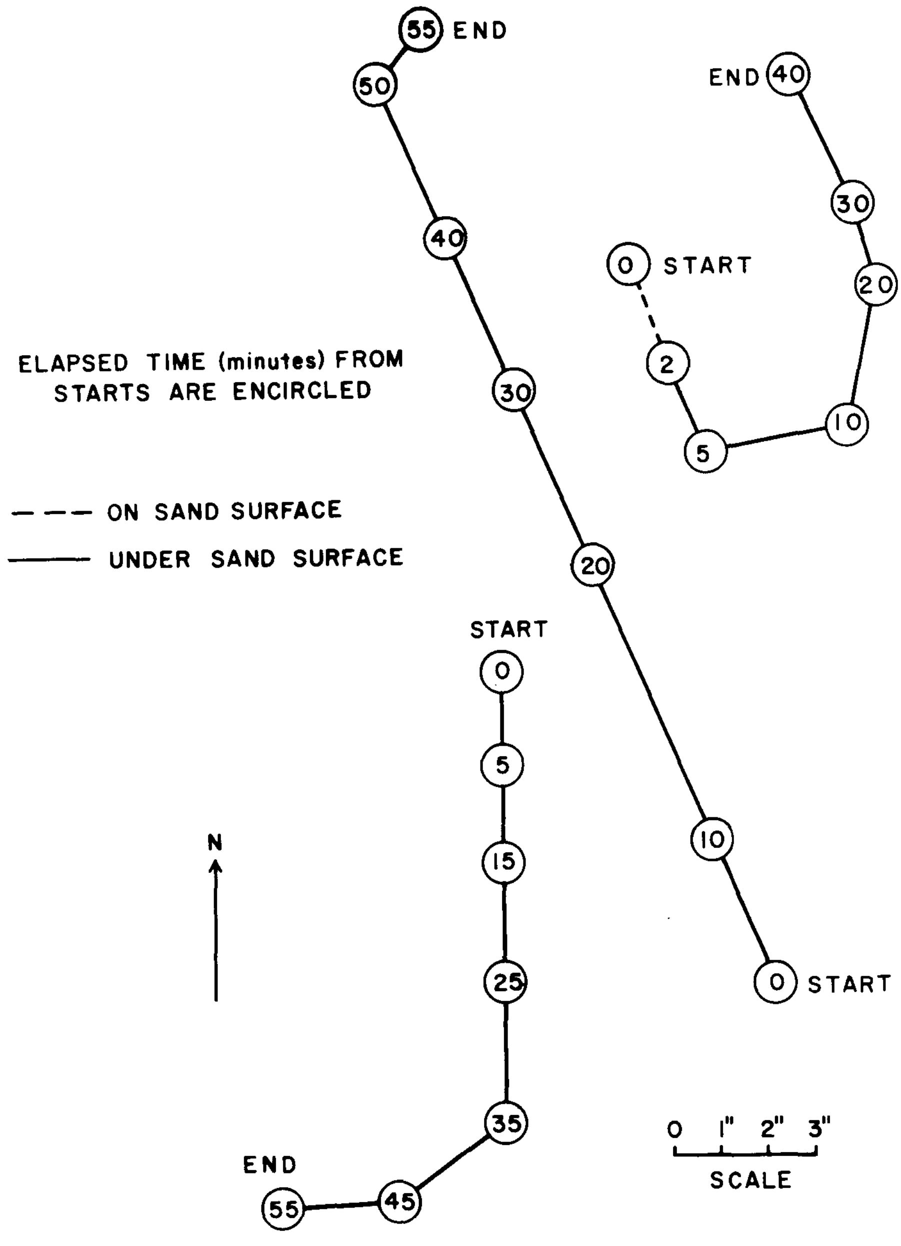
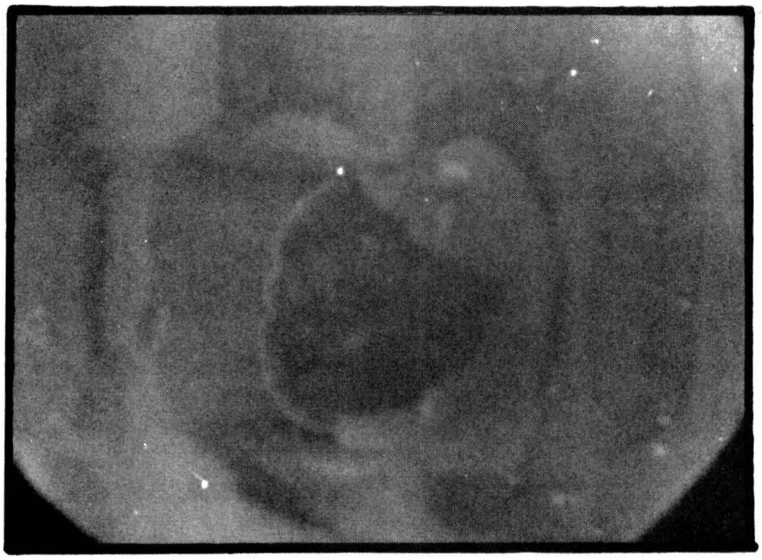


Figure 4.– Synoptic paths of three sand dollars within ten feet of each other. They were observed on Sept. 24, 1969 in a few inches of water located in study area north of Fisherman Island, see Figure 1.

Figure 5. - A series of photographs taken about five minutes apart through a view box fixed over a field of sand ripples. Moving on the surface, a three inch sand dollar flattens the ripples.

A1



A2

A3

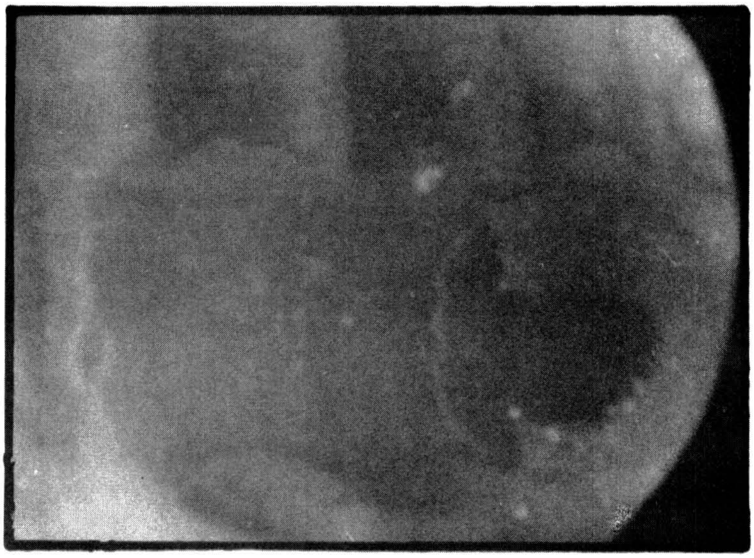
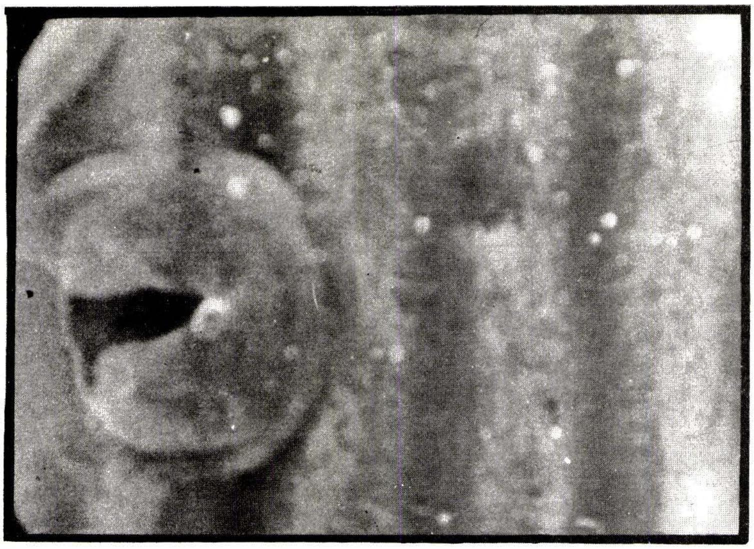
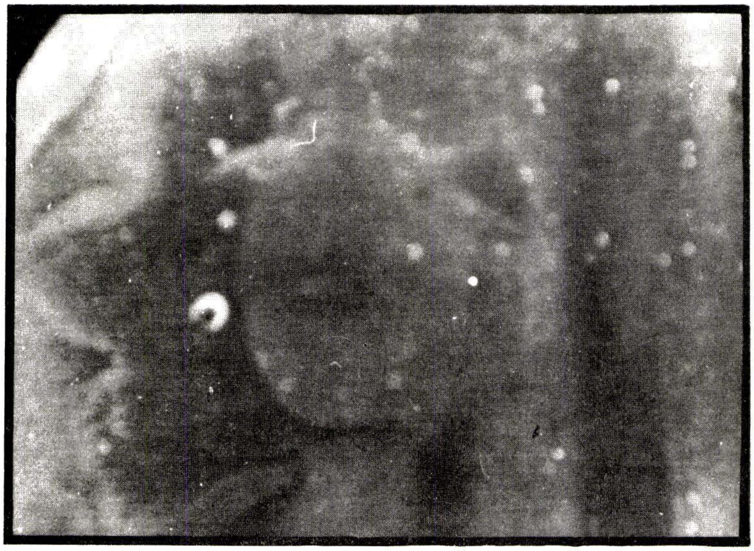


Figure 6. - A series of photographs taken about five minutes apart through a view box over a field of sand ripples. Moving beneath the surface, a three inch sand dollar flattens the ripples.


B1


B2

B3

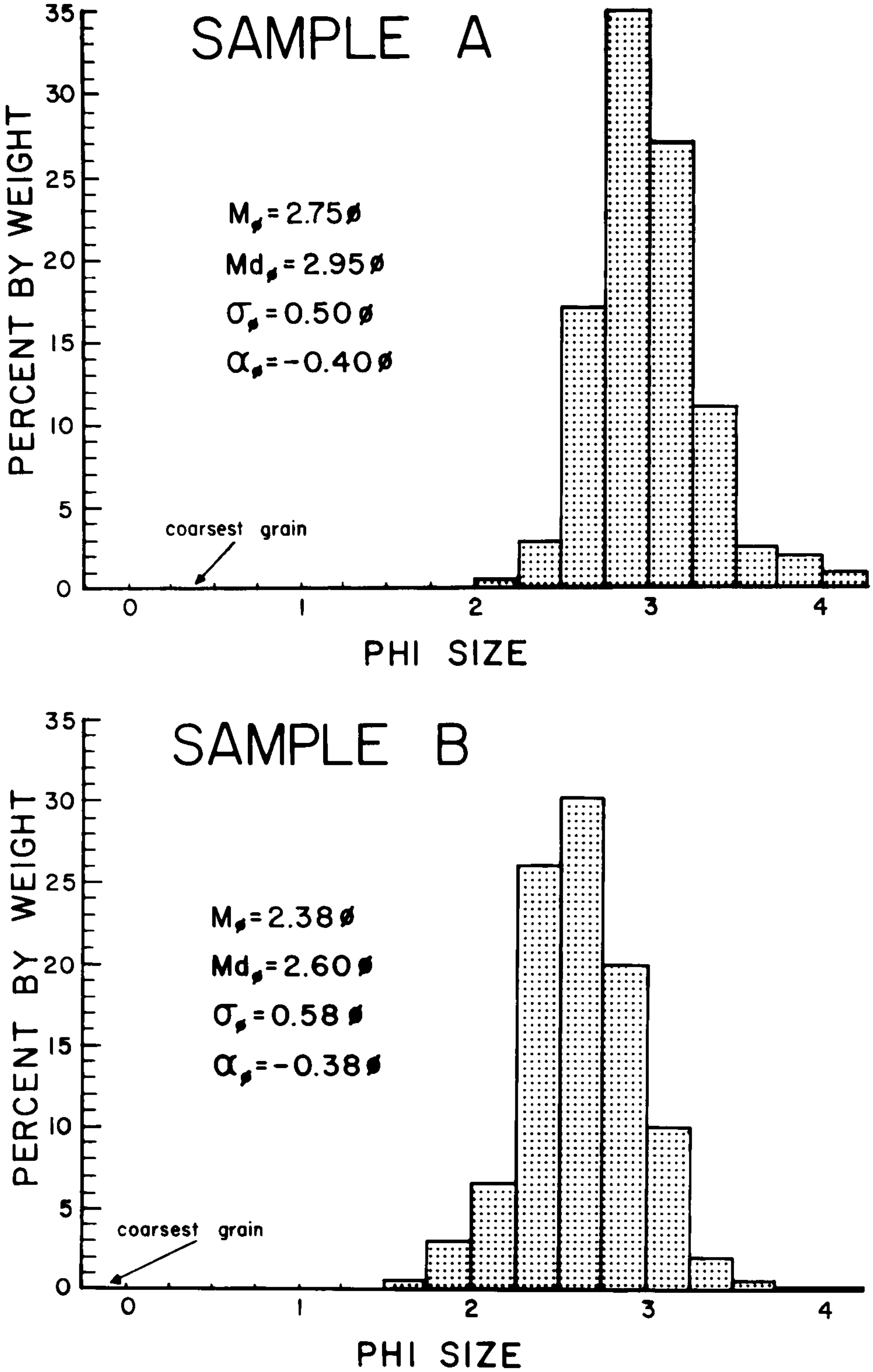
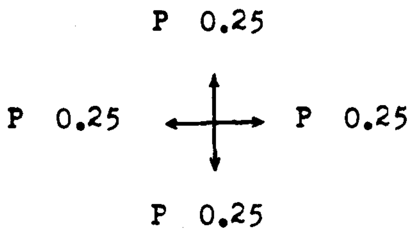
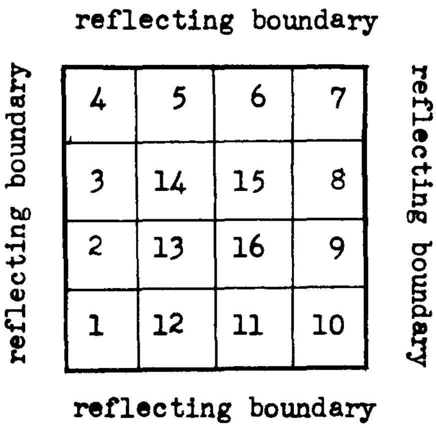



Figure 7.— Grain size frequency distribution histograms of two sediment samples. A. from an area devoid of sand dollars; B area containing them.



Four directions of movement are allowed with equal probability of movement for each direction.



The square area moved within has four reflecting boundaries as its perimeter. This area is divided into blocks, sixteen in the figure.

A move is made in one of the allowable directions from one block into an adjacent block or a reflecting boundary. Note that diagonal movement is not allowed.

Figure 8 . - An illustration of the concepts of movement and of the area moved within as used in the random walk model.

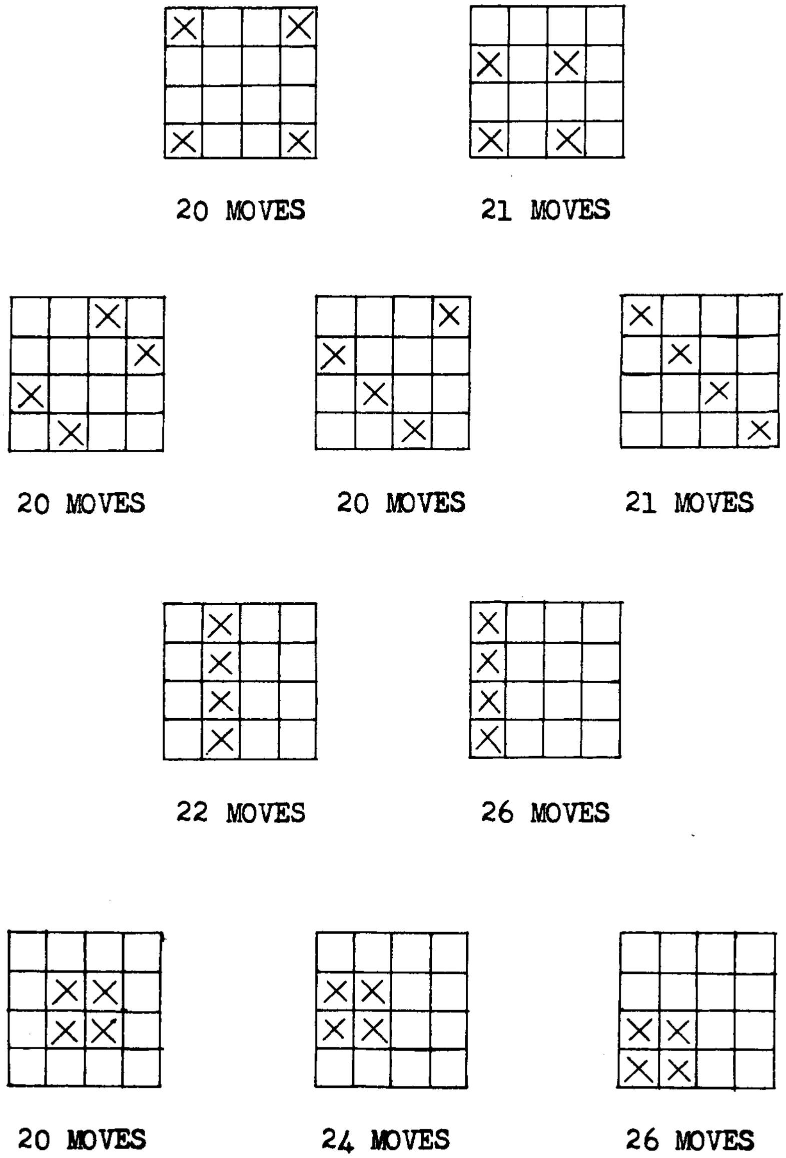


Figure 9. - An illustration of the connection between starting configuration and number of required moves. In the case illustrated, there are 16 blocks and 4 starters (X's in the figure). No more moves are made when entrance in all blocks has been achieved with a joint probability of 0.95.

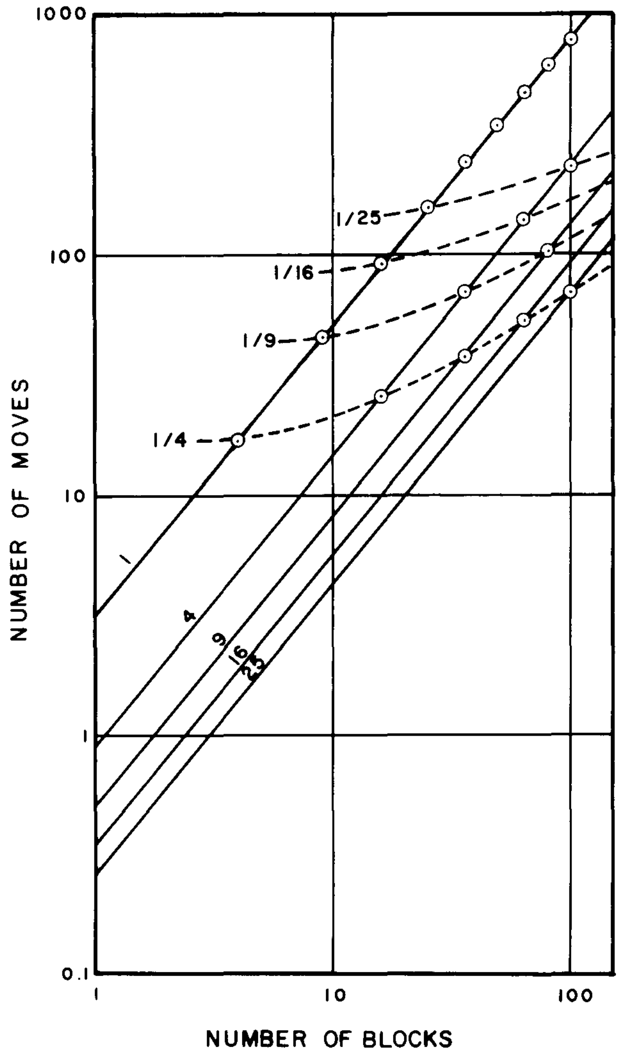


Figure 10.—A plot of the data from Tables 4 and 5
A solid line represents a constant number of starters.
A dashed line represents a constant ratio of the number of starters to the number of blocks.

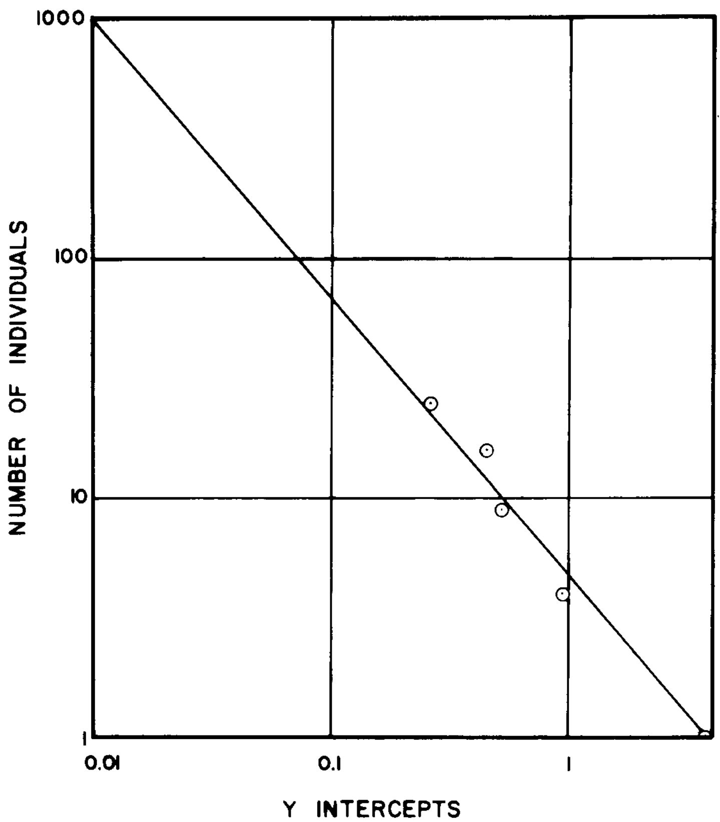
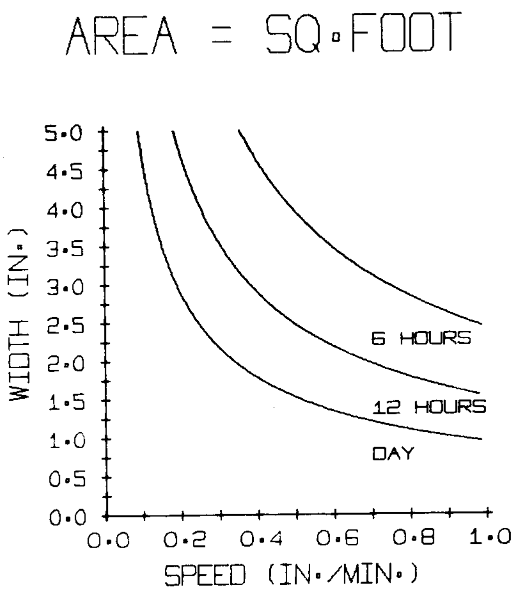
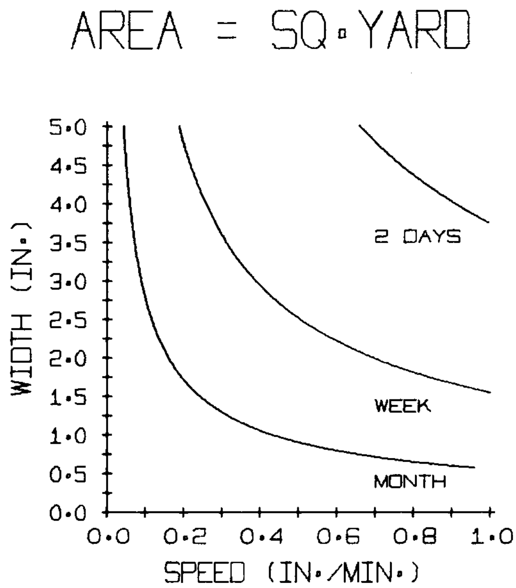


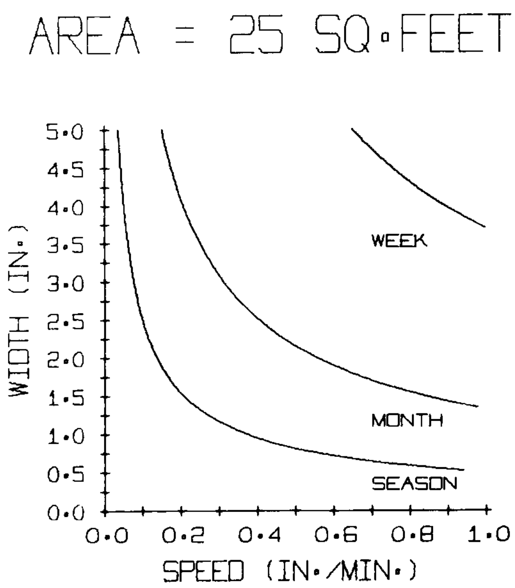
Figure 11.— A replotting from Figure 10. The y intercepts of the solid lines vs. the number of starters for the line.

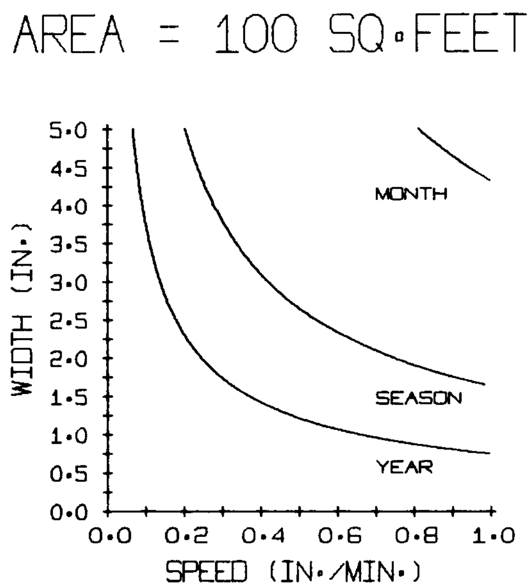
Figure 12. - A set of computer plots of sweep time presented as curves in units of hours, days, weeks, months, seasons, and years. Each page exhibits graphs for a constant number of sand dollars, but each graph on the page is for a different area. The x and y coordinates represent general ranges of size and speed of sand dollars.

ONE SAND DOLLAR PER UNIT AREA

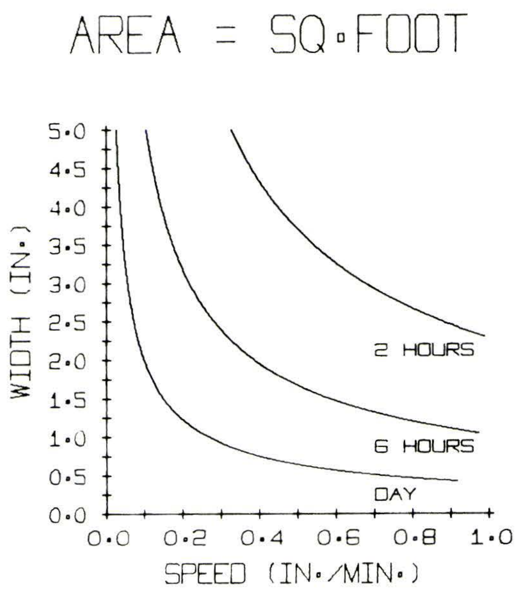


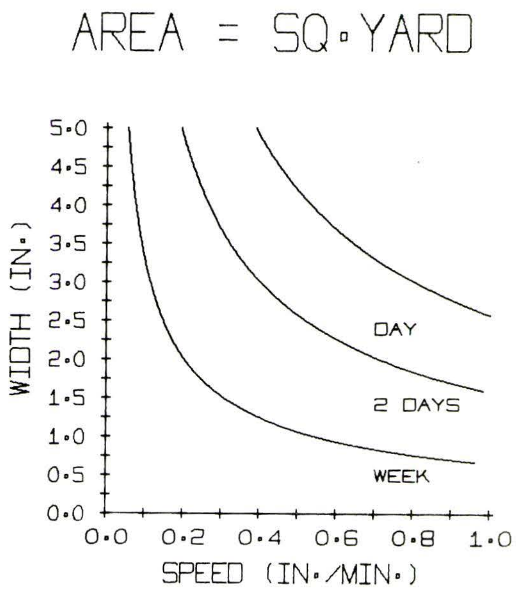


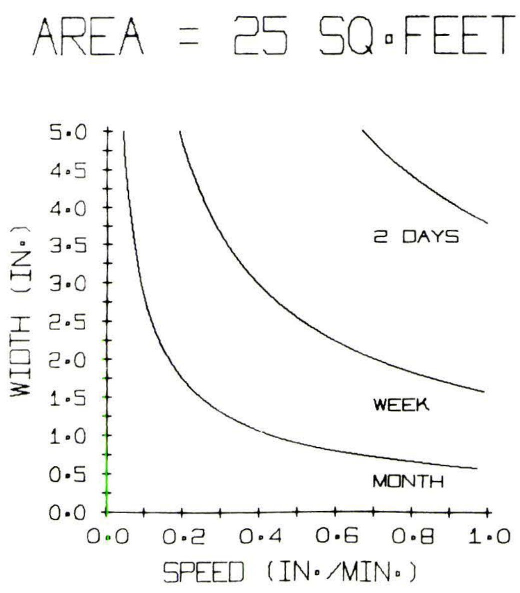


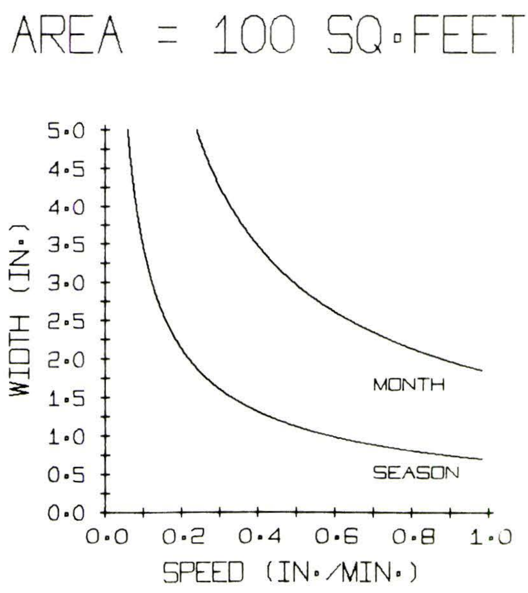


FIVE SAND DOLLARS PER UNIT AREA



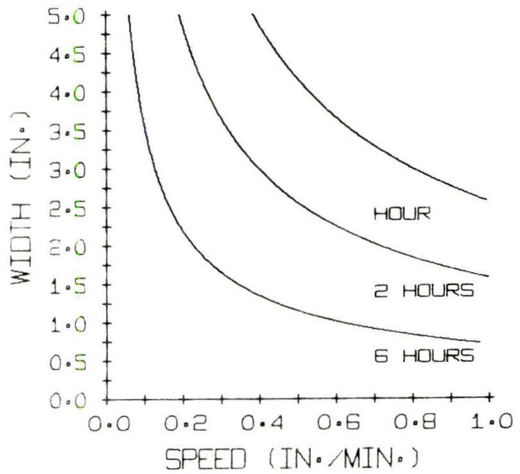




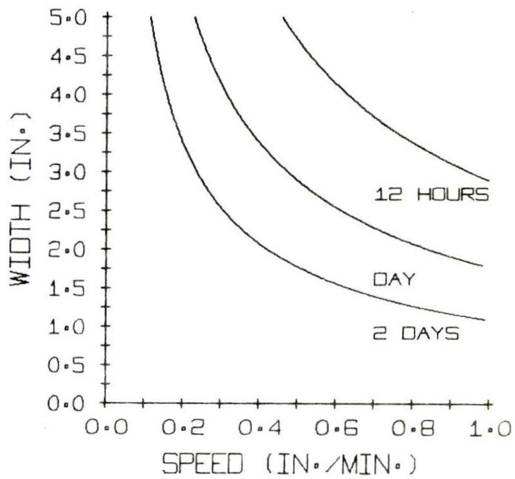


TEN SAND DOLLARS
PER
UNIT AREA

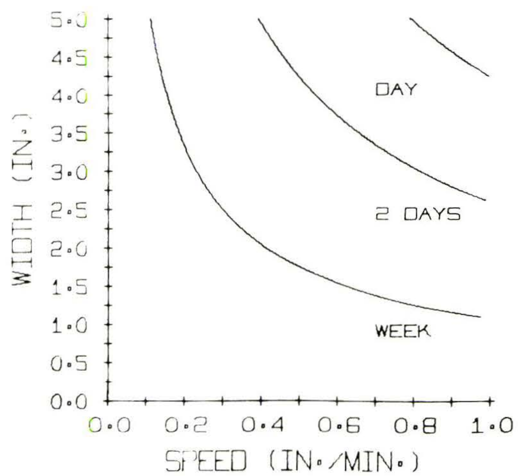
AREA = SQ.FOOT



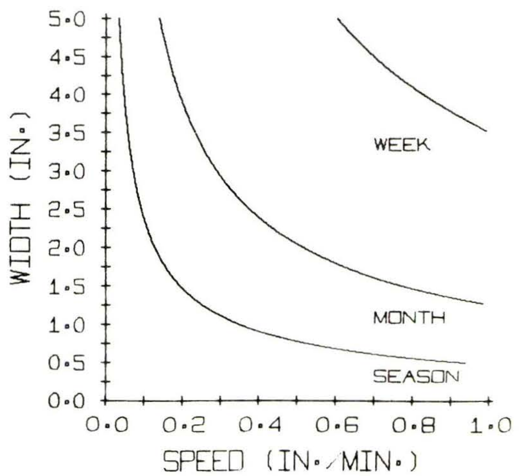
AREA = SQ.YARD



AREA = 25 SQ.FEET

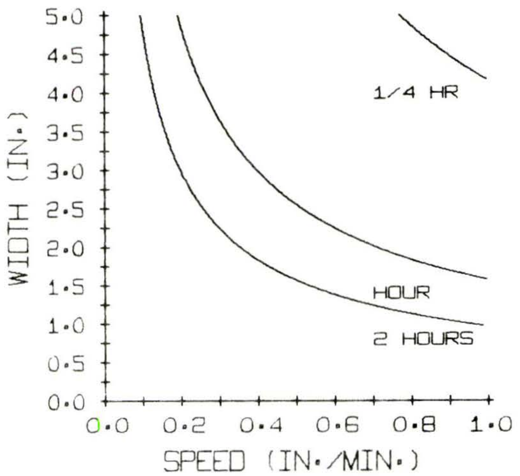


AREA = 100 SQ.FEET

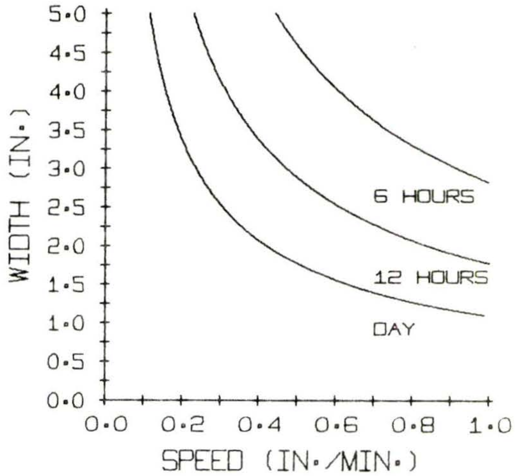


TWENTY-FIVE SAND DOLLARS PER UNIT AREA

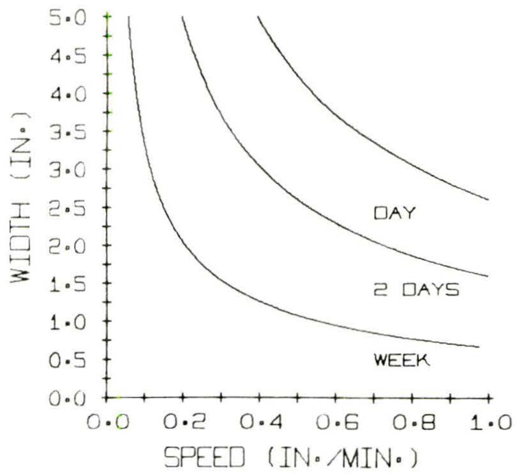
AREA = SQ.FOOT



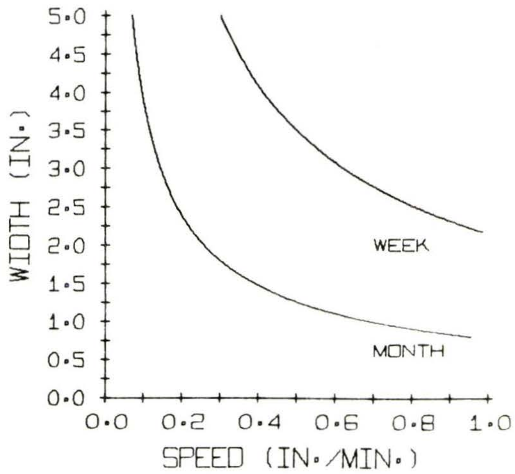
AREA = SQ.YARD



AREA = 25 SQ.FEET

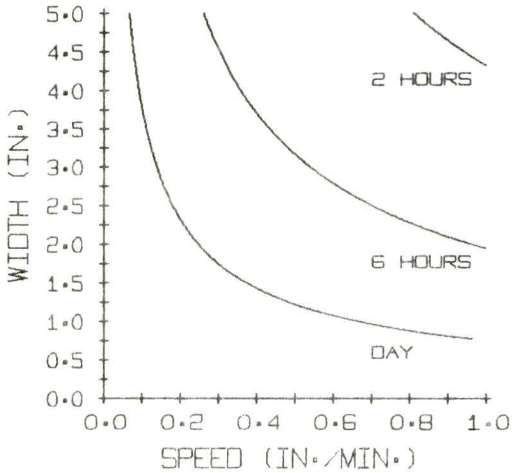


AREA = 100 SQ.FEET

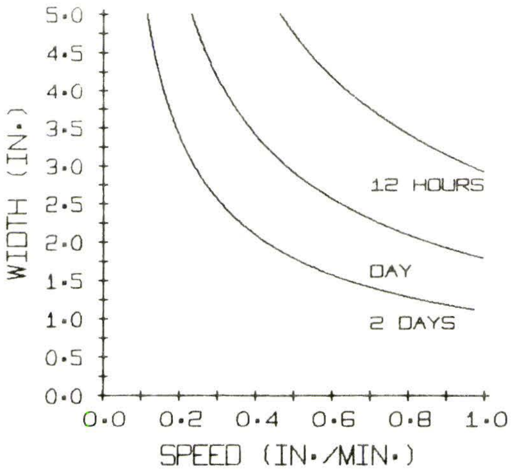


FIFTY SAND DOLLARS PER UNIT AREA

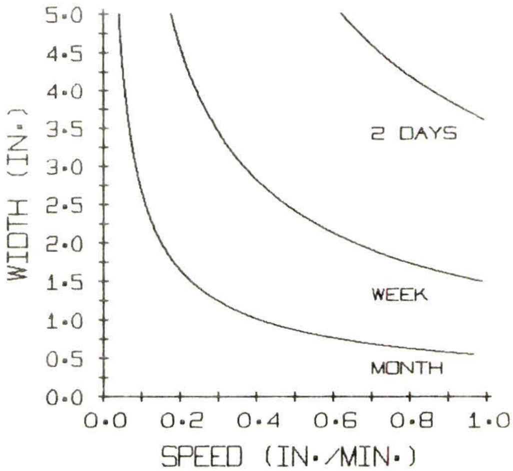
AREA = SQ.YARD



AREA = 25 SQ.FEET

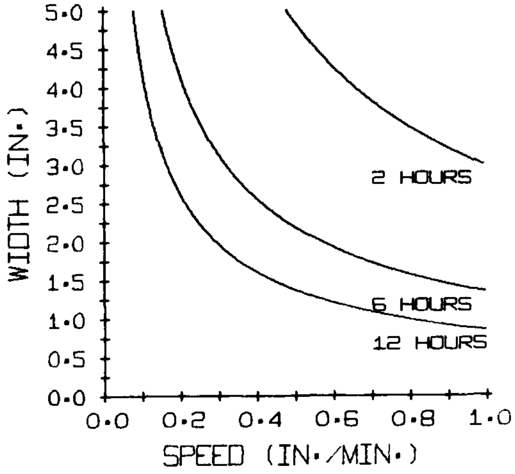


AREA = 100 SQ.FEET

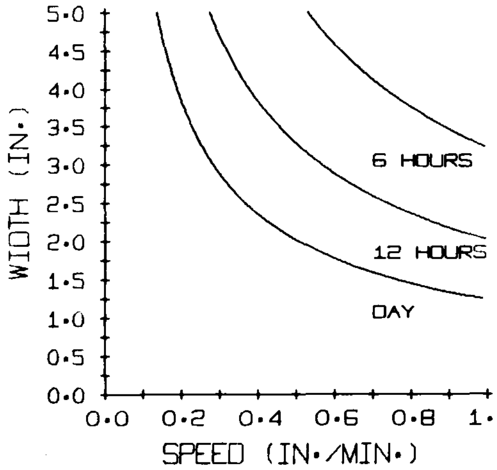


ONE HUNDRED SAND DOLLARS PER UNIT AREA

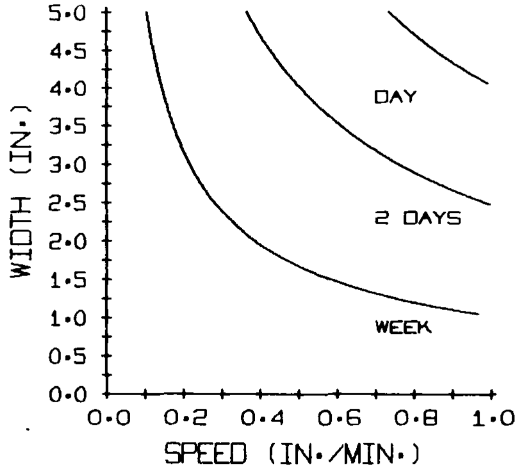
AREA = SQ. YARD



AREA = 25 SQ. FEET



AREA = 100 SQ. FEET



43,560 SAND DOLLARS
(ONE / SQ.FOOT)

AREA = ACRE

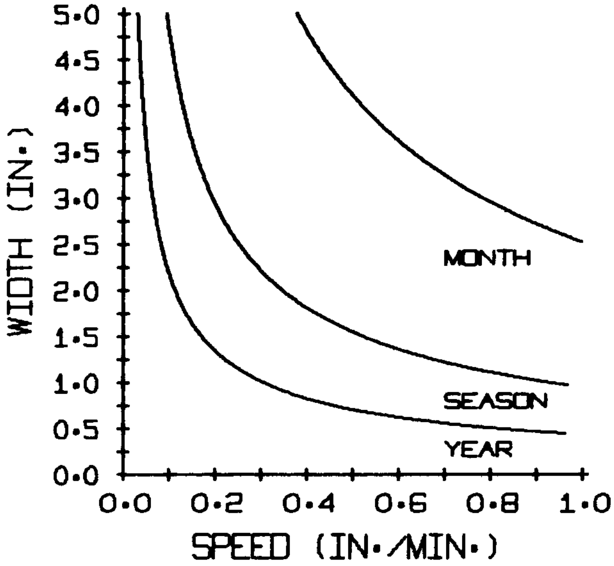


TABLE 1. - Number of sand dollars oriented in various directions.

Zero degrees is magnetic north.

Sept. 5, 1969

degrees	0	45	90	135	180	225	270	315
number	8	5	4	4	4	3	1	7

Sept. 12, 1969

degrees	0	30	60	90	120	150	180	210	240	270	300	330
number	1	7	1	1	2	2	2	1	0	2	1	0

Sept. 24, 1969

degrees	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
number	11	5	9	5	9	2	5	10	7	3	7	1	10	1	4	6

TABLE 2. - Average sizes and standard deviations of three samples and of their total.

DATE SAMPLE TAKEN*	NUMBER IN SAMPLE	WIDTH (inches) $\bar{x}$	WIDTH (inches) σ	LENGTH (inches) $\bar{x}$	LENGTH (inches) σ
Sept. 5,1969	36	2.72	0.35	2.57	0.32
Sept. 12,1969	20	2.66	0.46	2.48	0.45
Sept. 24,1969	96	2.71	0.26	2.53	0.26
TOTAL	152	2.71	0.31	2.55	0.30

*Locations shown in Figure

TABLE 3 . - Observed rates of movement of four different sand dollars of various sizes.

WIDTH (inches)	RATES OF MOVEMENT (inches/minute) TRIALS ON SURFACE 1	2	3	TRIALS UNDER SURFACE 1	2	3
2.0	1.0	0.75	---	0.5	0.5	---
2.5	1.5	1.5	1.5	---	---	---
2.5	1.5	1.5	0.75	0.5	0.5	0.5
3.5	1.5	1.0	---	0.5	0.5	0.5

TABLE 4 . - Moves needed by one starter to have made entrance into all blocks with the joint probability of 0.95.

NUMBER OF BLOCKS	MOVES NEEDED WHEN STARTING IN CENTER	CORNER
4	--	16
9	43	46
16	89	93
25	152	158
36	234	242
49	333	345
64	454	469
81	595	614
100	757	780

TABLE 5 . - Moves needed by more than one starter, all concentrated in corner blocks, to have made entrance into all blocks with the joint probability of 0.95.

NUMBER OF STARTERS	NUMBER OF BLOCKS	NUMBER OF MOVES
4	16	26
	36	71
	64	140
	100	232
9	36	38
	81	105
16	64	54
25	100	71