SURFACE-CURRENT STUDIES OF SAGINAW BAY AND LAKE HURON, 1956

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EXPLANATORY NOTE

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SURFACE-CURRENT STUDIES OF SAGINAW BAY AND LAKE HURON, 1956

by

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A B S T R A C T

Surface currents of the waters of Saginaw Bay and lower Lake Huron area were studied in the summer and fall of 1956. Drift bottles were used in Saginaw Bay and drift bottles together with the dynamic-height method were used in Lake Huron. A total of 2,650 drift bottles were released; 1,843 (69.5 percent) reply cards from the recovered bottles were returned.

Correlation appeared to be high in Saginaw Bay between direction of surface currents that moved these bottles and direction of winds. In Lake Huron this correlation was less apparent, although the drift of bottles was generally from west to east, seemingly under the influence of the prevailing westerly winds of this area.

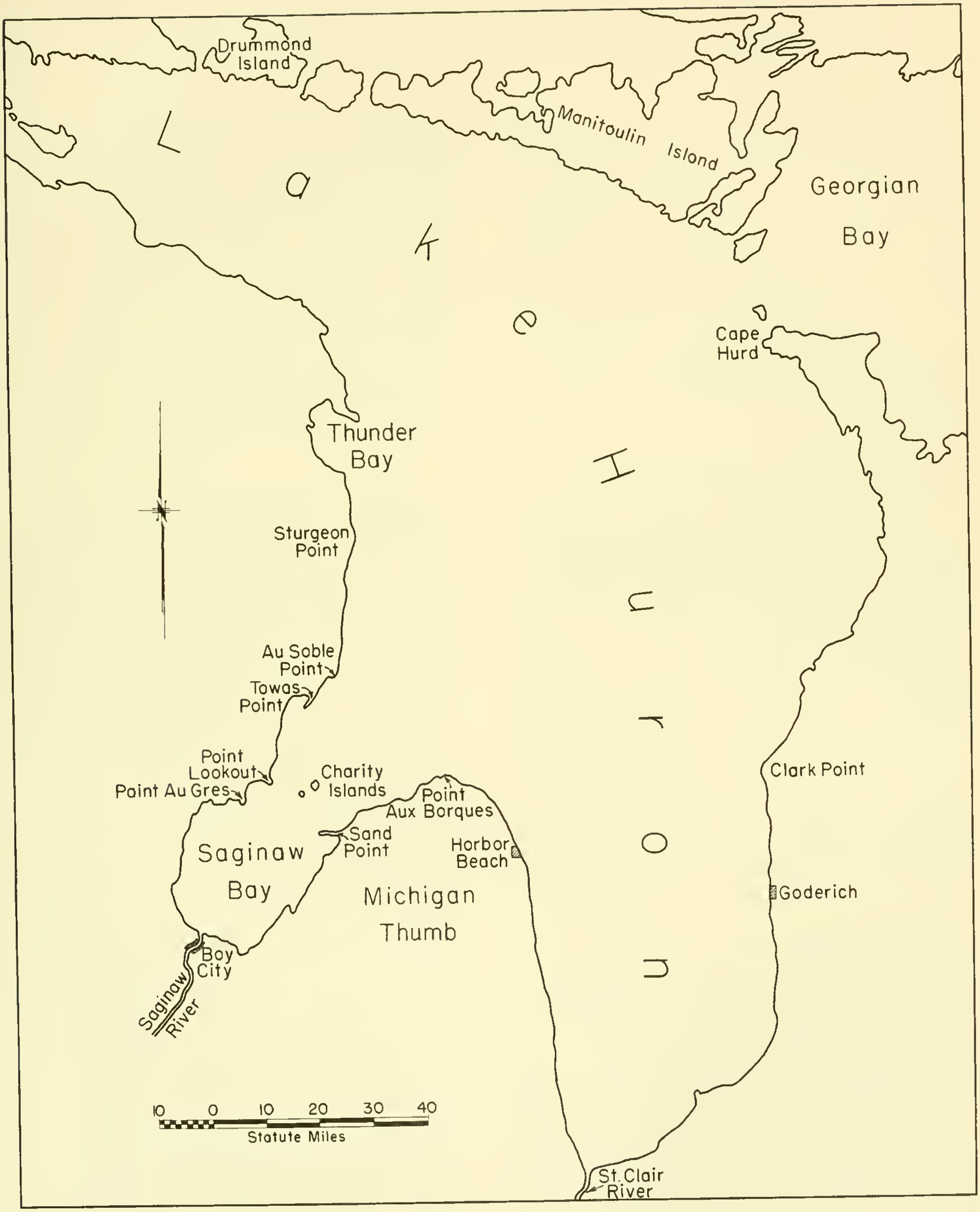


Figure 1.--Lake Huron and Saginaw Bay.

It is increasingly apparent to students of aquatic biology that water currents and movements of large water masses play a paramount role in the life cycle of many aquatic organisms. Water movements influence the distribution and ultimate survival of eggs, larvae, and adult aquatic organisms. The relation is direct when organisms are carried along actively by currents, and indirect when currents cause changes in environmental factors such as temperature, salinity, and other physical and chemical conditions. Although the direct effects are more obvious, the indirect influences may play an important role in survival and distribution of aquatic life.

At times movements of water masses can alter so adversely the habitat of fishes, especially those that live in a narrow environmental range, that kills of catastrophic proportions occur. The disaster which overtook the tilefish off the northeastern coast of the United States in 1882 was due to a sudden but temporary flooding of cold polar water into the warmer waters normally inhabited by this fish (Bigelow and Welsh 1925). An estimated 1 1/2 billion dead fish were sighted on the surface waters shortly after this calamitous event. Not only was fish life affected but certain invertebrates were exterminated by the cold mass of water. Outbreaks of red tide off the western coast of Florida are probably initiated by water masses which differ in salinity and chemical characteristics from the normal water off the Florida coast (Slobodkin 1953). Slobodkin believed that prediction of red tides would depend on more detailed knowledge of coastal drainage and hydrography, and that prevention of red tides may be possible, to some extent, by altering certain coastal drainage patterns.

The adverse effects of movements of water masses upon fish populations are probably matched by an equal number of favorable incidents. The 1904 year class of herring in the North Sea dominated the commercial herring fishery in that area from 1908 to 1919. This year class was prominent for other species also. Evidence indicated that the success of this year's hatch was due to an abnormally intense inflow of Atlantic water into the North Sea that carried with it either an abundance of the actual food required by newly-hatched fishes or provided certain nutrient salts resulting in a high abundance of basic food organisms (Tait 1952). According to Tait, there seems little room for doubt that the essential causes of fishery fluctuations lie in hydrographic conditions and that adequate observations of these conditions affords the surest means of anticipating these fluctuations. He perceived that the relationship of hydrography to fisheries is analogous to that of meteorology to agriculture.

In recent years, certain commercial fisheries of Saginaw Bay, Michigan, have deteriorated at an alarming rate. The annual commercial catch of the walleye (Stizostedion v. vitreum) has decreased in the last decade to such an extent that the economy of this fishery has been greatly weakened (Hile 1954). Many fishermen attribute the scarcity of the walleye in the bay to pollution. Production of lake herring (Leucichthys artedi) and whitefish (Coregonus clupeaformis) is also low. The yellow perch (Perca flavescens), on the other hand, are at such a high level in numbers that their growth is stunted (El-Zarka 1958). A fishery survey conducted with the study upon which this report is based revealed an abundance of alewives (Pomolobus pseudoharengus) and smelt (Osmerus mordax) but there is little commercial production of these species.

The U. S. Fish and Wildlife Service and the Michigan Department of Conservation conducted a cooperative limnological survey in Saginaw Bay and adjacent Lake Huron waters in the summer and fall of 1956 (fig. 1). The objectives of the study were to gain basic information on species composition and species inter- and intra-relationships, and to develop the possible causes of the fluctuations in the Saginaw Bay fisheries. As part of this project drift bottles were used to obtain information on the current systems and to determine the amount of water interchange between the bay and lake. This report analyzes the drift bottle movements in Saginaw Bay and Lake

Huron and summarizes briefly the use of drift bottles by other workers.

DRIFT-BOTTLE DESIGNS

History

Among the first recorded accounts of the use of drift bottles is that of Bernardin De Saint-Pierre who in 1784 recommended releasing floating bottles from time to time with each bottle carrying a note telling the day, latitude, and longitude of release (Rouch 1954). A French naturalist, Aimé, shortly before the middle of the nineteenth century released 50 bottles off the Algerian coast and subsequently obtained returns of 3 of them (Schmidt 1913). An interesting early record of drift bottles is that reported by Prince Albert I of Monaco; a bottle released toward the end of the nineteenth century in the Atlantic Ocean southwest of Ireland was recovered 646 days later on the coast of Tunis in the Mediterranean Sea (Schmidt 1913).

Evolution of current indicators since these experiments have been along two main lines: indicators of a stationary mechanical type that measure the current at a certain point; and passive objects carried along by currents. Since this project utilized the latter type, the following report is limited to passive drift units.

In 1892, 1893, and 1894 masters of some merchant vessels released nearly 5,000 drift bottles at various points throughout the Great Lakes (Harrington 1895). These bottles had no ballast or drags and each contained a reply card. Although the bottles floated low in the water, enough was exposed above the surface to cause Harrington to remark that the wind may have influenced their movements. He reasoned that bias to the results was not important since the wind that drifted the bottles would move the surface water in the same direction. He did feel, however, that wind caused the bottles to drift faster than the water but that the effect was slight.

From the use of plain stoppered bottles, it was but a short step to reduce the wind effect by the inclusion of a ballast to make the bottles float with only a small portion exposed above the surface. Garstang (1898) used ballasted "egg-shaped" soda-water bottles on the English Channel. They were 9 inches long and the upper half was painted red to make them conspicuous. Ballast consisted of lead shot held stationary in the bottle by paraffin to minimize displacement of the center of gravity. He concluded that movements of ballasted bottles were principally due to the force that local winds exerted upon the surface of the water, subject, in certain areas, to modification by tidal currents.

Drift bottles used in the Danish Oceanographical Expeditions to the Mediterranean Sea in 1908-1910 were ordinary champagne bottles, well corked, with the mouth dipped in pitch (Schmidt 1913). Some bottles were ballasted with sand; others had no ballast. Any difference in travel between bottles with and without ballast was not given in the results of the experiment. Schmidt believed that the wind had considerable direct effect upon the bottles. Platania (1923) in a further report on the Danish Expeditions concluded that drift bottle movements in the western Mediterranean did not reflect true currents, but were influenced primarily by the prevailing winds.

The travel of well-designed surface floaters, when interpreted properly, gives reasonably reliable information on surface currents at a particular time and place. Investigators, however, are frequently interested also in subsurface currents. To obtain information on subsurface currents, Bidder (Carruthers 1927) developed a "bottom trailer" bottle for use in the North Sea. The bottom trailer used by Nelson (1922) was a stoppered glass bottle, the neck of which carried a straight wire tail pointing in the direction of the long axis of the bottle. The bottle was weighted to have a small negative buoyancy in sea water. When released it sank to the bottom. Its descent stopped as the tip of the tail touched the bottom, and it drifted with the current in that position. The weight of the bottom trailer was adjusted so that the bottle weighed 1.7 grams more than the volume of sea water (at 8° C., specific gravity 1.0275) displaced by it. These bottles were expected to become entangled within the nets and trawls of fishermen and the reply cards subsequently to be returned by them. Carruthers (1947) reported that success in the use of "bottom trailers" had not been great because they "take sanctuary" between the sand ridges.

Various other methods have been used to reduce exposure of drift bottles to winds. Gilson (Carruthers 1930) experimented with coupled systems consisting of pairs of bottles, one bottle of the pair with positive buoyancy and the other of negative buoyancy, linked together by cords 3 meters long. In his experiments in the North Sea he noted a marked difference in rate of travel between simple surface floating bottles and his coupled systems. On occasion simple floating bottles and coupled bottles released at the same time traveled significantly different routes and directions. A similar coupled system was described by Sverdrup, Johnson, and Fleming (1942) in which the lower of the two coupled bottles contained a weak acid which in time corrodes a metal stopper, thus permitting sea water to fill the bottle and sink it. Fishermen are depended upon to return reply cards from bottles that become entangled in their nets.

One of the most popular methods of reducing direct influence of the wind is by using a metal drag that is suspended from the drift bottle by a length of wire. This arrangement not only reduces the surface area exposed to wind but also causes travels of the bottle to be affected by currents between the surface and the depth of the drag. Length of suspending wire can vary but most workers have used a wire in the neighborhood of 3 feet long. Mavor (1922), however, (Bay of Fundy) used drags suspended by wire 5.5 meters long. Webster and Buller (1950) in studying ocean currents off the New Jersey coast used both free bottles and bottles with drags suspended by a 4-foot wire. Their bottles released with drags attained a greater speed of transport than those without; furthermore, prevailing winds had little effect upon the direction of drift. Deason (1932) who released bottles with a drag suspended 3 feet below the bottle (Lake Michigan) concluded that the action of the prevailing westerly winds had much to do with the rate of and direction of surface currents. In Hudson Bay experiments, Hachey (1935) used a 3-foot galvanized wire to suspend a metal drag. He made no remarks concerning the circulation of waters other than the general circulation seemed to be counterclockwise.

Carruthers (1930) experimented with drift bottles on the North Sea to ascertain difference in the travels of surface floaters (ballasted and unballasted), drag-fitted bottles, and coupled bottles systems. Drag-fitted bottles were of two kinds: those with a metal drag suspended from a surface-floating bottle by a wire 3 feet long; those with a 9-inch-high, 6-inch-diameter toffee tin suspended by a 3-foot wire from a surface-floating bottle. The toffee tin contained a drift bottle and both the surface-floating bottle and the one in the tin contained reply cards. The coupled system consisted of two bottles, a bottle of negative buoyancy suspended from a surface-floating bottle by a 3-foot piece of stout sash cord. Carruthers found that in some instances unballasted surface floaters, ballasted surface floaters, and drag-fitted bottles put out at the same time and place showed significantly different movements. Only two replies were received from the coupled system--not enough to allow a valid comparison with the other returns.

In recent years drift cards in plastic envelopes, as developed by Olson (1951), have been looked upon with favor by some as a substitute for drift bottles. Olson used a polyethylene envelope 0.004 inch thick with the return card hermetically sealed within. His Lake Erie experiments indicated that the travels of these envelopes were not at the complete mercy of the wind. Some cards that were returned 18 months after release were still in good condition. In remarks on Olson's work, Verber (1953) wrote that drift cards were better than drift bottles since the cards are inexpensive and give greater accuracy in interpreting the surface flow because they are not exposed to the wind. He concluded that Olson's work proved a direct correlation between wind and surface flow in western Lake Erie and that the movements of surface water were wind controlled.

In Georgian Bay, Lake Huron, 3,000 drift cards similar to those developed by Olson (1951) were dropped from an airplane (Fry 1956). Polyethylene material, however, was only 0.002 inch thick and proved to be only moderately satisfactory because pinholes developed in the plastic from sand abrasion.

Drift cards were used by the Fish and Wildlife Service on Lake Superior in 1953 and on Lake Michigan in 1954. Few returns were obtained from these releases, and of those cards returned many were found water-soaked inside the polyethylene envelope. The polyethylene envelope was in some cases not sealed properly; and since a number of cards were found on the bottom off shore, it is possible that many of them sank before they reached land.

Bougis and Ruivo (1953) added ballast to the polyethylene-envelope type of float. Their "siphonophone" consisted of three parts: a polethylene envelope of 0.004 inch thickness that floats on the surface; the reply card within the envelope; and a drift with ballast. The drift was a ribbon of polyethylene 1.2 meters long and 8 centimeters wide attached to the polyethylene float. About 20 grams of lead ballast were placed at the lower extremity of the ribbon to make the drift sink into the water. Experiments on the Bay Banyuls, with drift cards only and "siphonophore" drifts, proved that the former followed the course of the wind closely, whereas the latter traveled at various angles with the wind and also moved much more slowly.

Drift bottles released in Saginaw Bay and Lake Huron

The drift bottle with metal drag was the design chosen for the Saginaw Bay-Lake Huron study in 1956 (fig. 2). It was evident from work by the Fish and Wildlife Service on Lake Michigan in 1955 that bottles with drags resisted direct effects of wind and presumably gave a better indication of water currents near the surface than did the ballasted bottles. Plastic envelopes were rejected for reasons already noted. A disadvantage of a bottle with the drag suspended several feet below the bottle is that the drag hits bottom in the surf zone and resists being washed ashore by the small waves characteristics of the Great Lakes. Observations have revealed that these bottles can be carried many miles in the surf, sometimes against the prevailing offshore current, before they are washed ashore. This disadvantage was eliminated, for the most part, by suspending the drag only 1 foot beneath the bottle instead of the usual 3 to 4 feet. The change was made after repeated tests with dye markers showed no discernable difference, under ordinary conditions, in water movement between 1 and 4 feet below the surface.

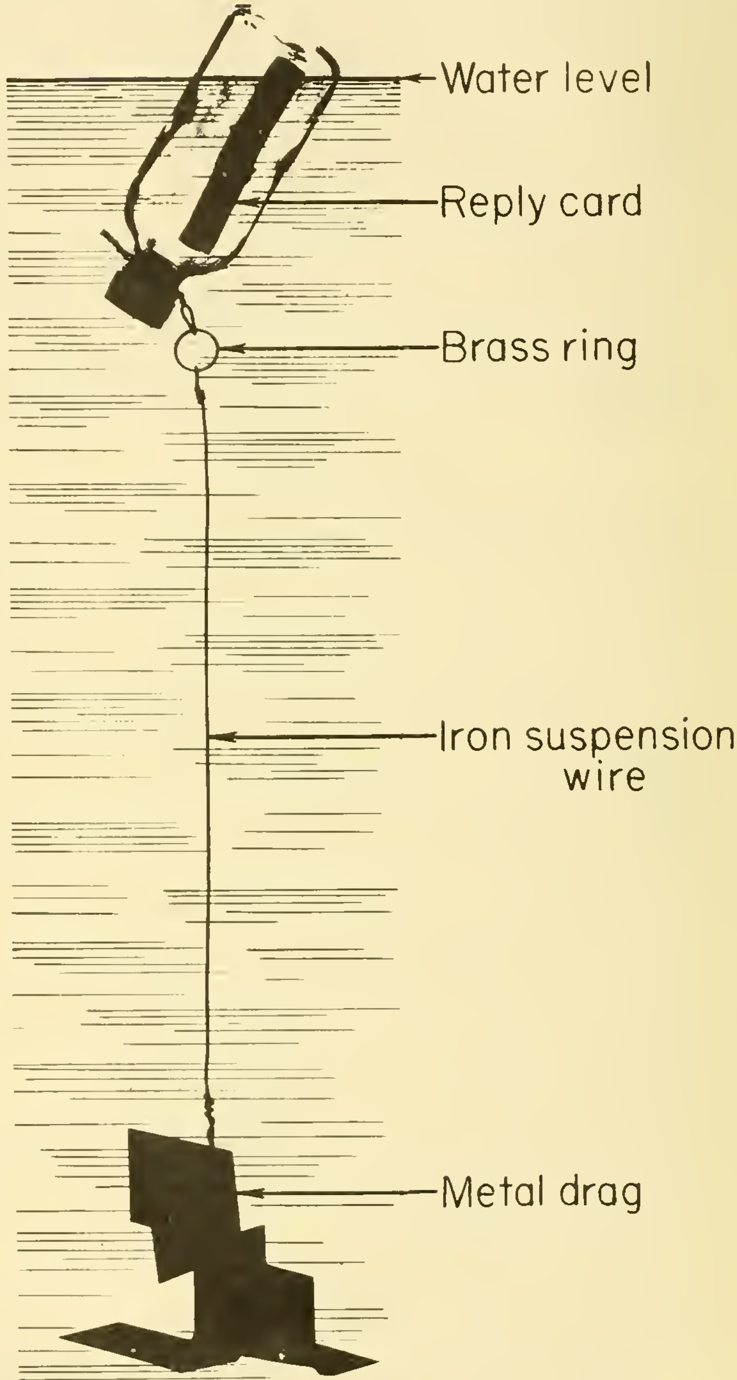


Figure 2.--Drift bottle as it appeared at time of release.

GREAT LAKES FISHERY INVESTIGATIONS
Ann Arbor, Michigan, U. S. A.

NOTICE TO FINDER Drift Card No. ....

This card is being used to study currents of the Great Lakes. Please fill in blank spaces. Mail every card you find. Canadian postage will be replaced. You will be told the time and place this card was released. Thank you.

Time of recovery: Date .... Hour .... a. m. p. m.

Was a metal fin attached to the bottle? ☐ Yes; ☐ No

Exact location card was found ....

....

Near ....
(City) (County) (State)

Remarks: ....

....

....

....

Please print: (Name) (Address)

U. S GOVERNMENT PRINTING OFFICE 16—71459-1

Please remove—read instructions

Figure 3.--Reply card similar to that placed in each bottle.

Reply cards (fig. 3) were placed in 4-ounce Boston-round bottles after which the bottles were stoppered with corks and the stoppered ends dipped into beeswax. Several drops of beeswax were then placed in the bottle caps and the caps screwed on the bottle. Drags were squares of 28-gage galvanized metal (4" X 4") so cut and bent that water movement from any direction struck areas of the three planes of the drag. During periods of high winds and heavy seas the horizontal fin of the drag would inhibit vertical movement so the bottle would be under the surface much of the time.

Studies on Lake Michigan in 1955 disclosed that many bottles lost their drags before they were washed ashore. The comments of finders indicated that the drags were lost because the soft iron suspension wire was broken at the neck of the bottle. The break was caused, most likely, by the bending of the wire as the bottle was moved by the waves. In the Saginaw Bay-Lake Huron project, loss of drags was reduced by placing a brass ring in the suspension wire at the neck of the bottle (fig. 2). The bottle could then move freely without bending the wire. As satisfactory as this arrangement proved to be, it did not end loss of drags. Of 1,076 bottles recovered within 29 days after release, only 18 (1.7 percent) had lost their drags. Of 523 bottles recovered after more than 29 days, 168 (33.3 percent) had lost their drags (table 1). Undoubtedly some of the 523 bottles recovered after

Table 1.--Loss of drags from drift bottles released in 1956 in relation to number of days between release and recovery

Number of days between release and recovery	Total number of bottles recovered	Bottles for which no data were given on drags	Bottles that had lost drags	
			Number	Percentage
0- 9	510	8	4	0.8
10-19	349	5	3	0.9
20-29	217	6	11	5.2
30-39	147	2	26	17.9
40-49	114	3	43	38.7
50-59	88	3	33	38.8
60-69	64	3	26	42.0
70-79	34	2	15	46.9
80-89	28	0	16	57.1
90-99	8	0	2	25.0
100-109	9	1	3	37.5
110-119	11	1	2	20.0
> 119	20	3	2	11.8
Not determined	4	0	1	25.0

29 days had actually landed long before their recovery. The small loss of drags from bottles out more than 119 days (11.8 percent--table 1) can be explained in part by the fact that many of these bottles were recovered at unfrequented places and may have landed many days before they were found. Duck hunters returned a number of these bottles in the fall from marsh areas. Even though the time out for the bottles was around 4 months, total travel from release point was less than 10 miles.

Remarks made by persons returning cards from bottles with lost drags indicate that the second weakness of the unit is in the attachment of the suspension wire to the drag. The weight of the drag and the stress imposed during the bottle's journey eventually cut through the wire. Because bottles in this study moved relatively short distances, the percentage of drags lost was small. In an experiment where bottles might be expected to be out for an average of over 30 days, the weakness in the suspension of the drag should be remedied.

The question often arises whether or not a reward should be paid for return of cards. A reward might increase the probability of the return of a reply card that has been found, and might encourage active searches for bottles. On the other hand, in projects where a large number of bottles are released the cost of rewards becomes prohibitive. Although the data (table 2) are far from conclusive, it appears that where rewards have been offered, the returns have not been consistently (12 to 57 percent recovery, average 29.0) greater than in experiments where rewards were not offered (3 to 67 percent, average 28.6). This may not, however, be an entirely fair comparison. Poor returns are to be expected in some experiments and those on which rewards were offered may have been this type.

Table 2.--Comparison of numbers of "bottles" released and percentage return for each of several areas

Investigator	Area	Number released	Percentage return	Type of drift unit	Reward
Aimé 1845 1/	Mediterranean	50	6	....2/...	None reported
Ayers *et al.* 1956	Lake Huron	1,641	10	Plastic toothbrush containers	None
Carruthers 1925	North Sea	1,275	67	Bottles plain	None reported
Carruthers 1927	English Channel	500	33	Bottles bottom-trailing and bottles plain	None reported
Daniel and Lewis 1930	Irish Sea	1,180	51	....2/...	None reported
Deason 1932	Lake Michigan	283	64	Bottles with drags	None
Fry 1956	Georgian Bay	3,000	10	Drift cards	None reported
Garstang 1898	English Channel	430	27	Bottles ballasted	None reported
Hachey 1935	Hudson Bay	500	5	Bottles with drags	None reported
Harrington 1895	Great Lakes	5,000	14	Bottles plain	None reported
Mavor 1922	Bay of Fundy	396	18	Bottles with drags and bottles plain	25 cents
Platania 1923	Mediterranean	515	26	Bottles ballasted and bottles plain	None reported
Ruschmeyer, Olson, and Bosch 1957	Lake Superior	1,000	33	Bottles ballasted	None reported
Schmidt 1913	Mediterranean	200	29	Bottles ballasted and bottles plain	None reported
Tait 1930	North Sea	4,825	23	Bottles ballasted	None
Tibby 1939	Pacific Ocean	5,943	3	Bottles ballasted	None
Uda 1932	Wakasa Bay	740	31	....2/...	None reported
Waldichuck and Tabata 1955	Strait of Georgia	237	57	Bottles ballasted	Small monetary award 3/
Webster and Buller 1950	Atlantic Ocean	489	12	Bottles with drags and bottles plain	50 cents
Wright 1955	Lake Erie	98	55	Bottles with drags	None reported

1/ Reported by Schmidt 1913; not seen by me
2/ Type of drift unit not specified
3/ Exact amount of reward not stated

No monetary rewards were offered in this study since remarks on returns of cards released in Lake Michigan in 1954-55 clearly indicated that finders were more interested in learning when and where bottles were released than in remuneration. Inquiry in shore areas showed that once a bottle was found word spread fast in the vicinity and searching for them quickly became a local pastime, merely for the satisfaction of finding a bottle that had drifted from an unknown point and for the feeling of participating in a scientific study. Business reply cards were used in this study so no postage was required when they were mailed in the United States. Where return of a card was at the expense of the finder, as when these cards were mailed in Canada, the sender was returned the postage due him. A letter was sent to the finder of every bottle telling of the time, place, and purpose of release. Any postage due the finder, was included with this letter.

RELEASES AND RECOVERIES

From June 5, 1956, until November 14, 1956, during nine cruises of the Fish and Wildlife Service research vessel Cisco, 2,200 drift bottles were released at 27 different stations on Saginaw Bay and adjacent areas of Lake Huron. In addition, on three synoptic surveys of Saginaw Bay on June 7, August 10, and October 30, 1956, the Fish and Wildlife Service research vessel Musky and a Michigan Department of Conservation patrol boat dropped an additional 450 bottles at 15 different stations. Altogether, 2,650 bottles were released at 42 stations (fig. 4). In Saginaw Bay the distance from any one point to a release point did not exceed 6 miles. Releases were more widely spaced in the adjacent waters of Lake Huron. It was not the intent of the investigation to make an intensive study of Lake Huron proper; rather we wished to study Saginaw Bay and its relation to the lake.

It is common in drift-bottle work to receive reply cards from bottles recovered months and even years after the date of release. The value of a recovery in the determination of currents decreases the longer the bottle is out in excess of actual drifting time. In areas where ice forms yearly, the possible effects of the spring ice breakup upon bottle movements preclude sensible analysis. To eliminate the latter problem and to eliminate other questionable records, bottles recovered after February 28, 1957, were not used in analysis. As of that date,

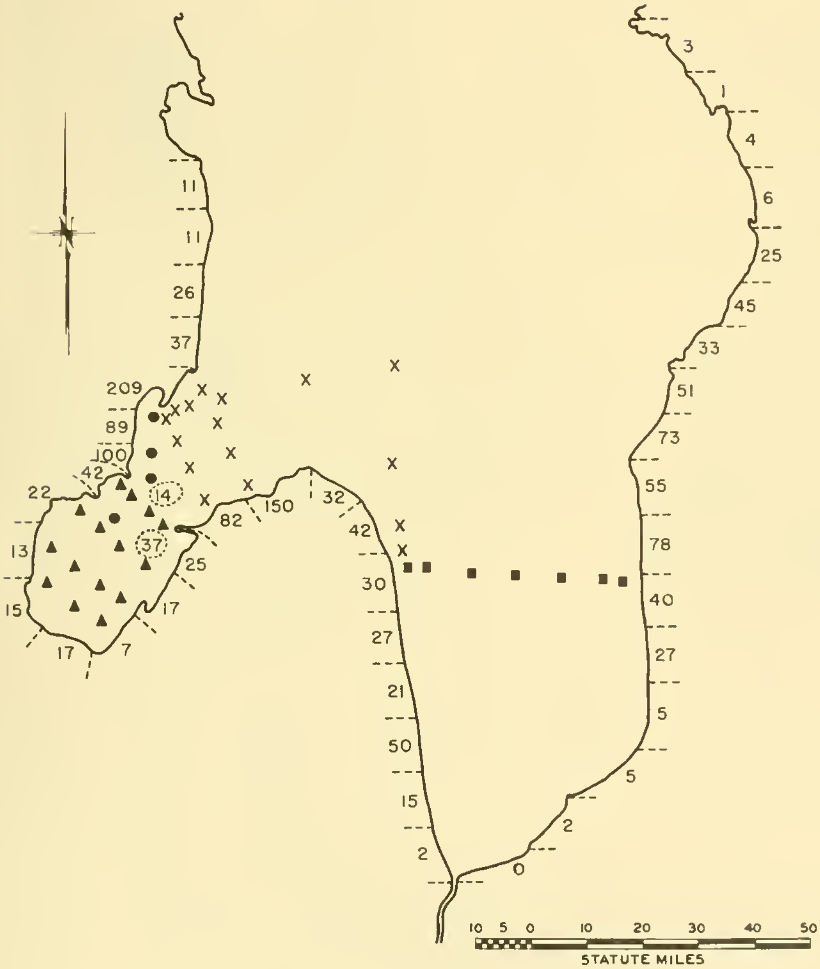


Figure 4.--Drift bottles released at 42 stations in Saginaw Bay and Lake Huron during 1956 and relative abundance of recoveries along the shoreline. Triangles indicate stations where 30 bottles were released, squares 40 bottles, X's 80 bottles, and circles 160 bottles.

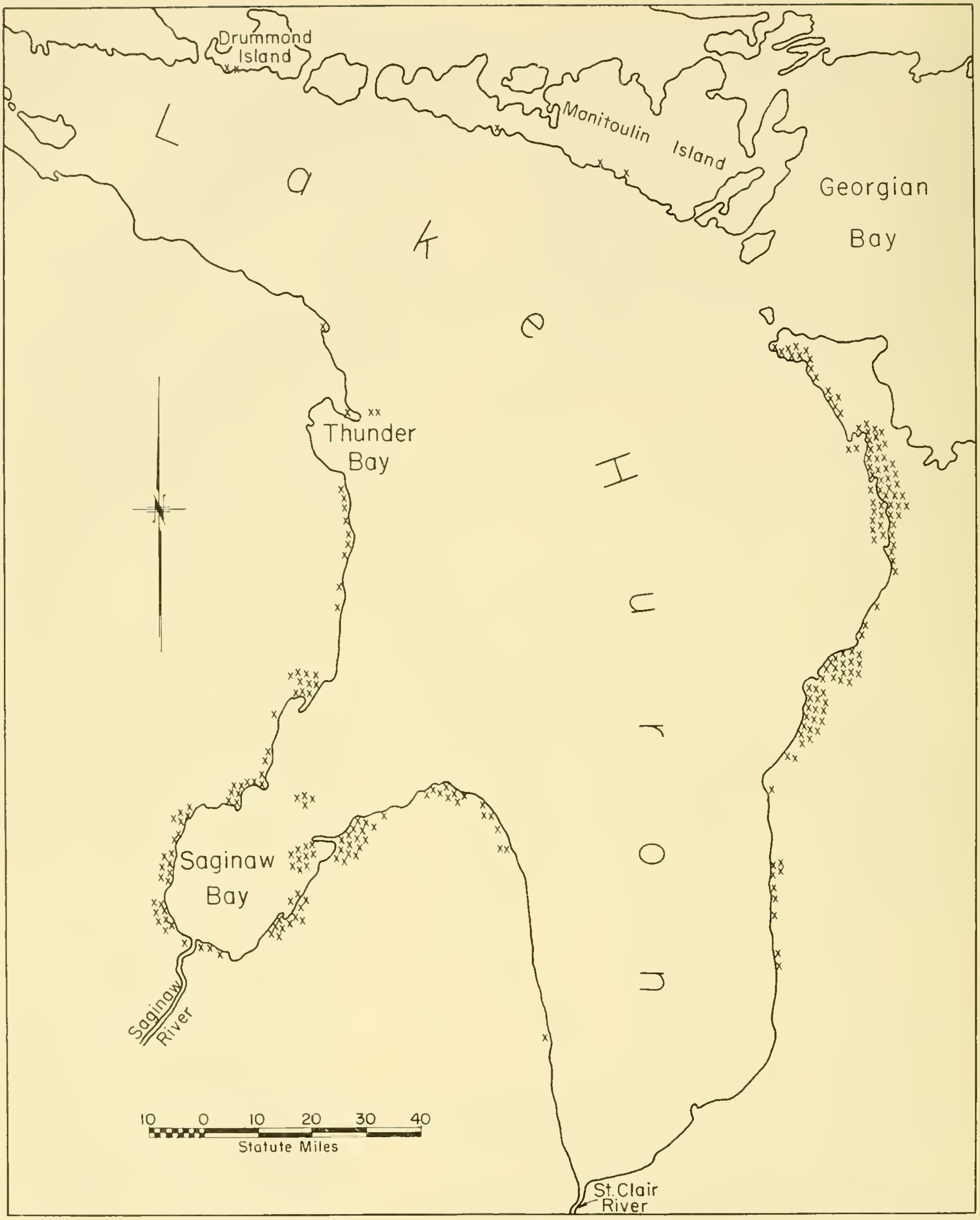


Figure 5.--Location of recoveries of drift bottles found after February 28, 1957.

returns had been received on 1,603 bottles; 60.5 percent of the total released. By December 1, 1957, an additional 240 reply cards had been returned (fig. 5) giving a total return of 69.5 percent--a very high percentage in comparison with returns in other studies (table 2). The percentage return of bottles released during any one cruise in this investigation decreased as the season progressed (table 3).

Table 3.--Returns of bottles released in 1956 from each of nine different cruises of the Cisco and from three cruises each by the Musky and Michigan Department of Conservation Patrol Boat

[Returns from bottles recovered after February 28, 1957, are not included]

Cruise	Date	Number of bottles released	Number returned	Percentage return
I 1/	June 3-11, 1956	350	262	74.9
II	June 19-July 2, 1956	310	232	74.8
III	July 11-23, 1956	240	171	71.3
IV 1/	July 31-August 13, 1956	460	299	65.0
V	August 21-September 2, 1956	240	155	64.6
VI	September 11-24, 1956	310	145	46.8
VII	October 2-15, 1956	240	125	52.1
VIII 1/	October 23-November 5, 1956	460	211	45.9
IX	November 13-21, 1956	40	3	7.5
Total		2,650	1,603	...

1/ Cruises during which the Musky and Michigan Department of Conservation patrol boat participated

Recoveries of bottles were for the most part highest over weekends (table 4). This trend was especially noticeable in late summer and early fall. During June, July, and August, the beaches and shores of the lake were apparently well covered throughout the week. After the vacation season ended, however, the shores were visited more frequently on weekends.

Recoveries before February 28, 1957, were made from a point 5 miles north of Sturgeon Point on the western shore of Lake Huron down through Saginaw Bay, the lower lake area, and up the eastern shore of Lake Huron to Cape Hurd (fig. 4). Several areas, however, yielded surprisingly few recoveries. Returns were especially light from the southeasterly corner of Lake Huron (fig. 4).

Table 4.--Percentage distribution of recoveries of bottles within the week in the various months of recovery in 1956

Day	June	July	August	September	October	November	December
Monday	9.0	6.3	10.8	4.7	11.7	2.1	12.9
Tuesday	15.7	8.8	7.7	6.3	3.9	5.3	12.9
Wednesday	12.4	9.2	7.0	9.0	7.8	3.7	9.7
Thursday	15.7	10.1	9.2	8.6	9.7	17.0	16.1
Friday	11.4	33.7	22.1	11.4	7.0	7.6	9.7
Saturday	19.4	16.2	20.6	27.9	35.9	34.0	2.6
Sunday	16.3	15.8	22.7	32.0	24.0	30.3	36.1
Total recoveries	196	246	314	293	305	200	35

The number of returns from any particular area depends on two major factors. First, of course, bottles must actually wash ashore. The numbers that do are determined by water movements and shore configuration. Second, the bottle must be seen and picked up. Apparently all shore areas were covered to some extent, especially during the vacation period, but the distribution of resorts and beaches is by no means uniform. Consequently, the recovery records do not give a precisely accurate measure of actual landings. I believe, however, that within reasonable limits they are quantitatively dependable, at least for central and southern Lake Huron.

Five returns made after the "cut-off date" of February 28, 1957, are of particular interest because the recovery points were so far removed from the rest. All five were released during the fall of 1956. Apparently, travel of these bottles was influenced by water circulation resulting from the strong southeast, east, and southwest winds that blew during the fall which would account for their travel to Drummond and Manitoulin Islands (fig. 5). It is conceivable that a number of bottles landed on these and other islands that rim the northern boundaries of Lake Huron, but because the shores are so little frequented only a few were found.

Table 5.--July 31, 1956, wind data from Coast Guard Stations on Saginaw Bay and Lake Huron

Hour	Tawas Point	Bay City	Harbor Beach
0400	S 5	NNW 18	S 16
0800	S 10	NW 16	SE 10
1200	SW 5	NW 10	Calm
1600	SE 2	N 6	SE 16
2000	N 2	N 12	S 5
2400	NW 5	N 6	NW 5

WIND DATA

After many years of work on the North Sea, Carruthers (1947) emphasized the importance of keeping suitable records of wind for use with studies of water movements. Wind data for this investigation were taken from Coast Guard Stations on Lake Huron and Saginaw Bay. (Other stations were held to be too far distant for the records to be useful in this study.) At no time were bottles dropped more than 50 miles from a source of wind information. The Tawas Point, Bay City, and Harbor Beach Coast Guard Stations submitted wind data consisting of six observations daily, that is, an observation every 4 hours. The wind direction and velocity were recorded for each observation at each station and a prevailing wind vector for the day at each station determined. A wind track based on these vectors was used in interpreting drift-bottle movements.

Even though the area studied lies within the belt of prevailing westerlies, frequent wind changes occur with the passage of the many pressure systems through the lakes areas. These changes are of paramount importance in affecting surface-water flow. In addition, there may be some tendency for offshore breezes at night and onshore breezes during the daytime. Because of these frequent wind changes, local winds at stations no more than 50 miles apart may be blowing from nearly opposite directions at the same time (table 5). These differences in wind direction among the stations are more common during periods of light, variable breezes. During strong blows and gales the wind direction is less likely to differ between stations.

Although the prevailing winds can differ between stations (fig. 6), the wind tracks in 1956 taken over periods of a month, were similar (fig. 7). Similarity among stations was greatest for August, September, October, and November and least in June and July when winds were usually light. This seasonal trend has prime significance in

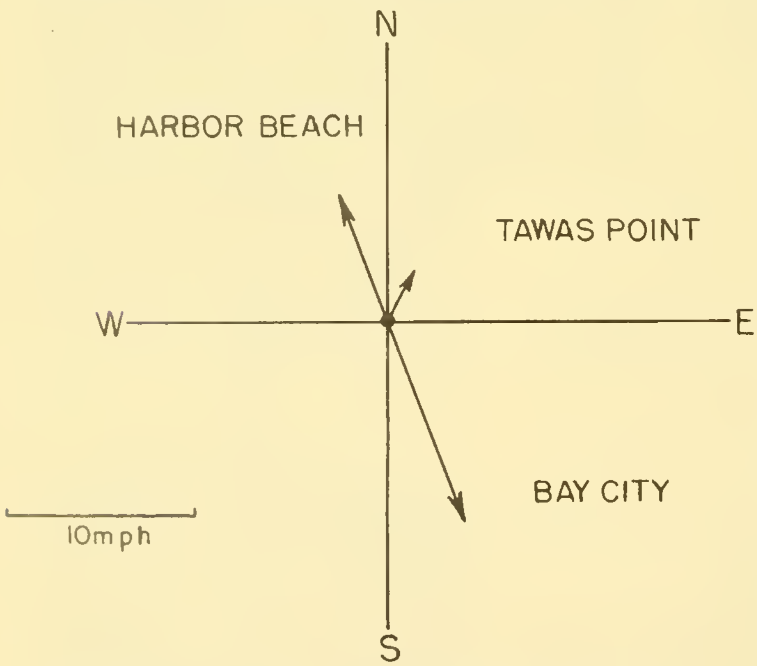


Figure 6.--July 31, 1956, wind vector at the Tawas Point, Bay City, and Harbor Beach, Michigan Coast Guard Stations.

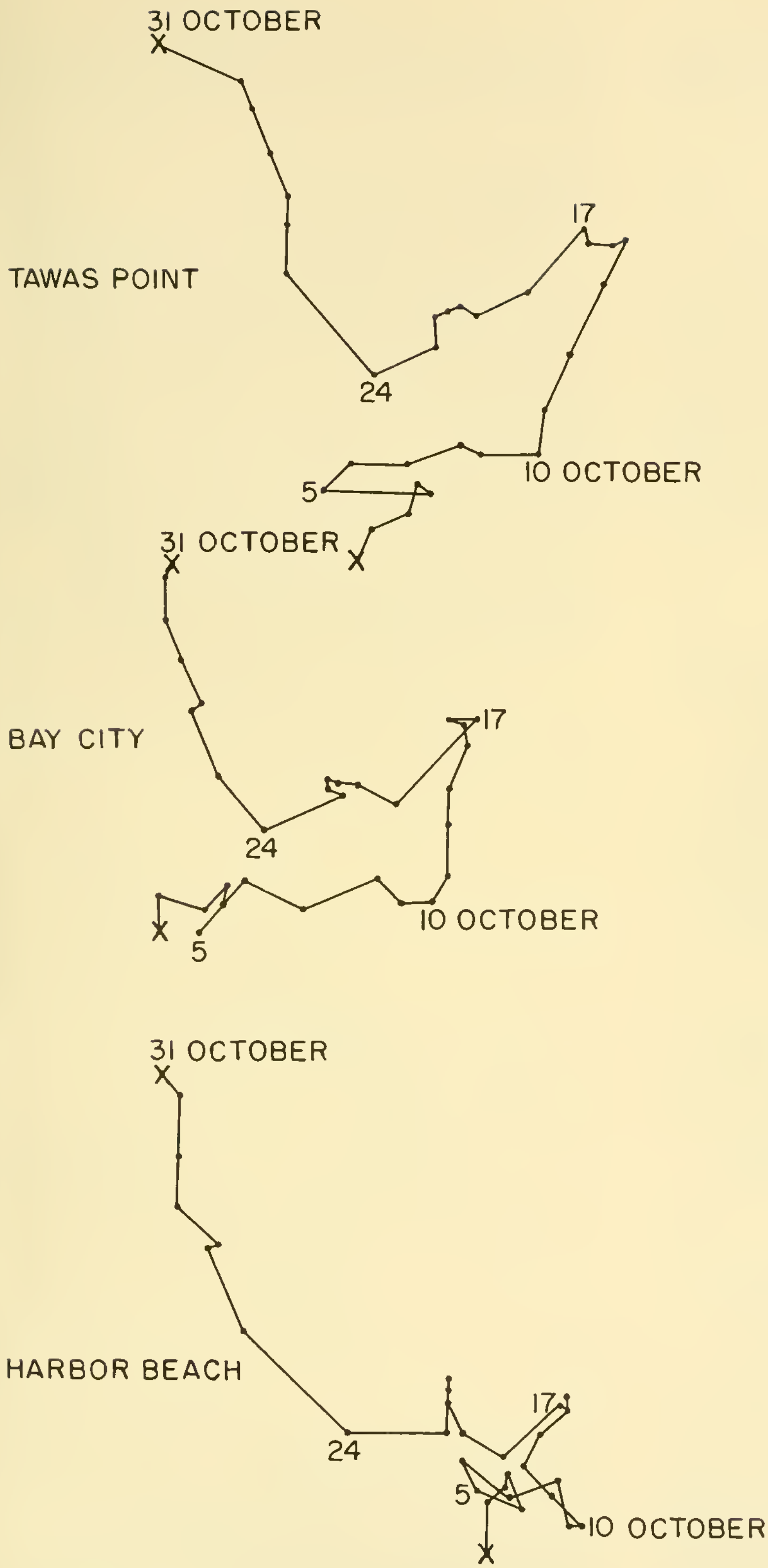


Figure 7.--Prevailing wind vectors for October 1956, at Coast Guard Stations bordering Lake Huron.

determining the procedure to be followed in the interpretation of effects of wind on water movement. The direction of the wind and direction of the movement of a bottle were correlated over periods of several weeks, regardless of the station for which the track was used. On the other hand, for study of short-term movements, it is desirable to use wind data from the station closest to the path of drift. It may be of some significance that movements of bottles that agree least with wind movements were those dropped farthest from any source of wind information.

WATER MOVEMENTS OF SAGINAW BAY

General features of the Bay

According to the Great Lakes Pilot, 1956, "Saginaw Bay, the largest indentation along the west shore of Lake Huron, has a width at its entrance between Pointe aux Barques and Au Sable Point of 26 miles, and from this line southwesterly to its head at the mouth of Saginaw River the distance is 51 miles. Its minimum width is 13 miles, between Sand Point on the east and Point Lookout on the west in the outer portion of the bay; but, owing to the very shallow bank extending from the easterly shore to beyond the Charity Islands, and to the shoal projecting from Point Lookout, the deep channel at this point of least width is contracted to a width of about 1 3/4 miles. The water level in Saginaw Bay is subject to sudden changes due to the wind, a northeast gale driving the water into the bay so as to raise the level at the mouth of Saginaw River 3 to 4 feet sometimes in less than as many hours, while a southwest wind lowers the level at times sufficiently to cause large vessels to ground in the channel."

Of the several tributaries

to Saginaw Bay, the Saginaw River at the southwestern end is the largest. It follows that the net flow of water must be from the southwestern end of the bay northeastward into Lake Huron.

The greater portion of the bay is less than 20 feet deep. It is only near Lake Huron at the mouth of the bay that a well-formed, persisting thermocline is present in the summer and early fall. Temporary stratification does, however, occur within the bay during the summer. In 1956 a thermocline developed in certain inner areas but it was ill-defined and temporary. Approximately 25 percent of the total area of the bay became stratified and almost all of this area was at or near the mouth.

Previous studies

Both Harrington (1895) and Ayers et al. (1956) were concerned primarily with circulation in Lake Huron proper, although the latter released "bottles" in the bay, and both had recoveries here. According to Harrington (1895) the most marked feature of the drift in Lake Huron is the stream passing southward along the west shore and crossing the mouth of Saginaw Bay. The few bottles that entered the bay during his investigation landed in the northwestern and southeastern sections. He did not comment on circulation within the bay.

The Saginaw Valley Project is of interest here even though no current studies were made (Adams 1937). For the summer and fall of 1935 and the summer of 1936, it is apparent from the study that there was little or no correlation between chloride concentrations in different areas of the bay and wind direction.

Ayers et al. (1956) noted changes in circulation at the mouth of the bay in different months. They believed that in June 1954 there was inflow on the north side and outflow along the south side. Some inflow in July was thought to be subsurface with outflow spread over much of the surface. Conditions in August were held to be similar to those of July. They conjectured from their limited data that Saginaw Bay may behave like a simple estuary of the same geographical orientation; hence, in the autumnal circulation there would be inflow at all levels along the north side and a similarly distributed outflow on the south side. They thought that the winter circulation might be the same as that in the spring or fall.

Drift-bottle movements in 1956

In our investigations, analysis of the drift-bottle returns from releases in Saginaw Bay confirms the belief of Ayers et al. (1956) that no one stable surface-current pattern exists within the bay. In fact, results disclose more variability of the surface currents than their studies were able to show. It appears that the dynamics of the bay are closely related to the highly variable meteorological conditions of this area and that the surface currents are in a continuous state of change. For this reason, we must state specifically under what conditions any particular surface-current pattern was found.

It is possible in Saginaw Bay for completely different current patterns to exist

Figure 8.--Typical surface-current flow for Saginaw Bay in the summer of 1956.

on succeeding days. In the summer of 1956 surface currents did at times approach a state that might be called "typical" for the bay (fig. 8). Yet this system was in a continuous state of readjustment to changing winds and no single surface-current pattern persisted over an extended period. Movements of bottles, released on August 10, give a good indication of surface currents under fairly stable westerly winds (fig. 9). Of 230 bottles released on this day only one was recovered on the western shore. Its travel cannot be determined since it was out 99 days before recovery. Very likely it first traveled easterly under the west winds, became entangled in marsh weeds along the eastern shores and then was refloated by strong easterly winds and carried across the bay to the western shore.

Under the influence of prevailing easterly winds, surface currents travel westerly in the bay as is demonstrated by the recoveries from bottle releases on October 12 and 13 (fig. 10). Although releases were made at fewer stations on these dates than on August 10, it is clearly evident from the recoveries that southeast, east, and northeast winds caused a general westerly surface drift.

To indicate more clearly the relationship between local winds and drift-bottle travel, the release and recovery points of the drift bottles have been plotted, along with the winds that blew a short time prior and subsequent to release (Appendix). As examples, three typical stations in the bay have been chosen [an inner-bay station, fig. 11; mid-bay station, fig. 12; and outer-bay station, fig. 13 (see pages 14 and 15)], and drift-bottle travel will be discussed on the basis of information from releases at these stations.

Nineteen recoveries were made from the

Figure 9.--Surface currents in Saginaw Bay determined from travel of drift bottles released on August 10, 1956, during a period of moderate westerly winds.

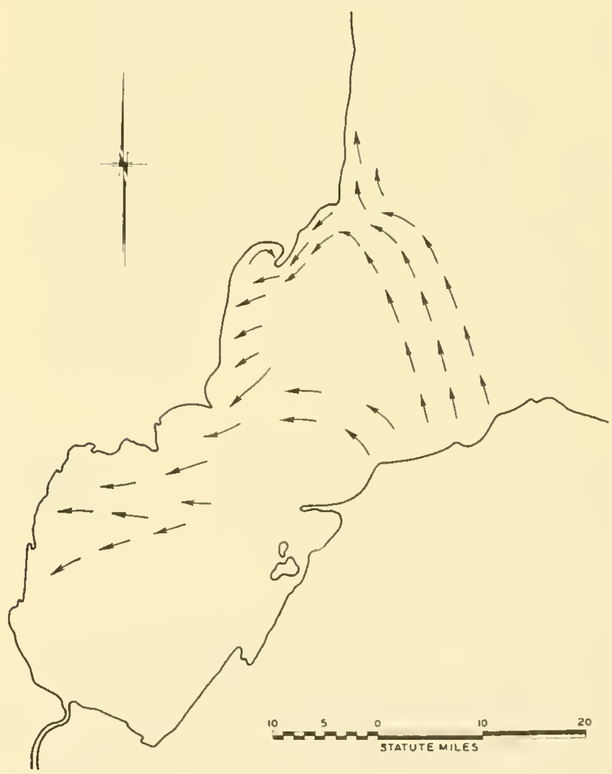


Figure 10.--Surface currents in Saginaw Bay determined from travel of drift bottles released on October 12-13, 1956, during a period of strong southeast-northeast winds.

30 releases at the inner-bay station (fig. 11). It is apparent that no single surface circulation could have existed throughout the summer and fall seasons to give such a pattern of recoveries. On the June 7 (fig. 21 A) and August 10 (fig. 43 A) releases, the direction of drift was to the northeast, presumably resulting from prevailing southwest winds at these times. Two days after 10 bottles were released on October 30 (fig. 68 A), moderate northeast winds caused currents that carried all but 3 of the bottles ashore to the southwest.

The 27 recoveries from the 30 releases at a mid-bay station show a greater dispersion than those recovered from the releases at the inner-bay station (fig. 12). Subsequent to June 7, at which time 10 bottles were released, the net wind vector was to the north. The resulting water movement accounts for the recovery of the 2 bottles found to the north of the release point (fig. 23 B). The 7 bottles recovered at least 49 days after release to the east and southeast appear to have drifted in this direction because of the net winds to the southeast for the period of time they were adrift (fig. 23 B). The 8 recoveries from the 10 releases on August 10 were to the east and southeast (fig. 45 B). The net wind vector for the period of time these bottles were drifting was to the east. The 10 bottles released on October 30 landed to the northwest of their release point (fig. 69 C). Apparently these bottles were carried with water moved by the winds that blew the day of and the day after release.

The 60 recoveries of 80 bottles released from an outer-bay station substantiate the theory that surface-current flow was unstable during this study (fig. 13). Recoveries from releases at this station

Figure 11.--Location of 19 recoveries from 30 drift bottles released at an inner Saginaw Bay station. Ten releases were made on June 7, August 10, and October 30, 1956. A triangle shows release point; X's mark recovery points.

Figure 12.--Location of 27 recoveries from 30 drift bottles released at a middle Saginaw Bay station. Ten releases were made on June 7, August 10, and October 30, 1956. A triangle shows release point; X's mark recovery points.

were made not only from widely scattered areas in Saginaw Bay but also from many points along the shore of Lake Huron. All 10 bottles released from this station on June 7 were recovered from the Tawas Bay area to the northwest within a short distance of one another (fig. 24 B). After release of these bottles, winds were variable for 3 days; next the wind was to the northeast for 3 days; the wind to the southwest a week after release apparently caused the bottles to land in and around Tawas Point. Bottles released on June 29 were recovered for the most part on the eastern side of the Michigan Thumb (fig. 30 B). The net wind to the southeast most likely caused currents that carried the bottles to this area. The widely scattered points of the 7 recoveries from the 10 releases on July 18 follow well, with one exception, the wind track (fig. 36 B). The only logical explanation for the recovery

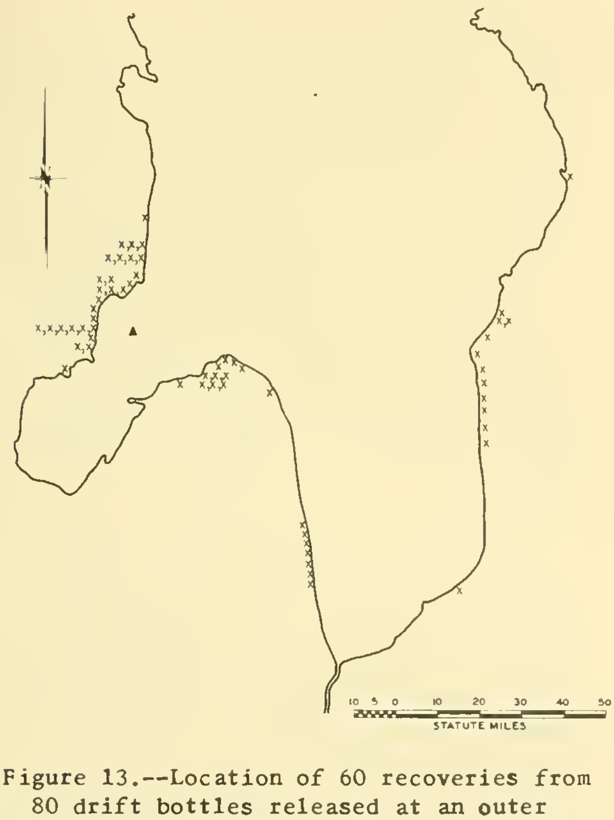


Figure 13.--Location of 60 recoveries from 80 drift bottles released at an outer Saginaw Bay station. Ten releases were made at 8 different times from June through October 1956. A triangle shows release point; X's mark recovery points.

on the Michigan Thumb after 27 days is the influence of a current entering Saginaw Bay from Lake Huron. The recoveries from releases on August 10 (fig. 46 B) and August 30 (fig. 52 B) indicate that surface currents flowed toward the east in August and September. Westerly winds prevailed these months. Bottles recovered from releases on September 21 (fig. 59 B) and October 12 (fig. 63 A) apparently were carried by currents caused by east and south winds, respectively. The recoveries from October 30 releases (fig. 70 A), although scattered widely, correspond well with wind direction. Apparently the bottles drifted into the bay where one was deposited on the west shore. A reversal in wind direction then drove the bottles over to the Michigan Thum where they landed near the mouth of the bay.

It is evident from the foregoing discussion that the surface currents of Saginaw Bay are closely related to the winds and consequently are highly variable. This dependence of currents on wind was closest for the inner reaches of the bay. Near the mouth of the bay a few bottles were found, the movement of which could not be explained by local wind action (fig. 33 B). Wind direction here at the time of release was to the northeast. The 3 bottles that landed within a day of release, however, traveled to the southeast at least 90° to the right of the wind vector. This variation most probably was brought about by a strong current entering the bay from Lake Huron, causing the bottles to drift at right angles to the wind. Additional variations were noted around Tawas Point and the area northeast of Sand Point.

Surface currents in the bay apparently orient to changing winds in a short period of time. For 2 days prior to release and on the day of release of 10 bottles northeast of Point Lookout, winds were from the south (fig. 32 B). The day after release the south winds diminished and changed to north. Surface currents had to reorient to the north winds in a very short time in order to cause the bottles to land as indicated. For 4 days prior to release of 10 bottles south of Point Au Gres on October 30, strong southerly winds blew (fig. 69 A). The day after release the south winds moderated and the second day after release changed to north. The surface currents had to reorient rapidly to the north wind to cause southwest drift of bottles, one of which was recovered 4 days after release.

The time required for the current to orient to the wind is dependent, of course, upon the strength of the wind and the existing flow pattern. In an area such as Saginaw Bay where a consistent current pattern does not exist, it seems possible that a surface current might change in response to a rapidly changed strong wind in a matter of hours.

No attempt was made to study subsurface currents. The Ekman spiral (Sverdrup, Johnson, and Fleming 1942) is frequently mentioned in explanations of surface and subsurface currents. According to this theory, surface currents on the northern hemisphere are directed 45° to the right of the wind, while at greater depths the current turns more to the right and the velocity decreases. Near the bottom of the friction layer the currents are low in velocity and move opposite to the wind direction. This theory, however, presupposes conditions of equilibrium, a state that is not reached in Saginaw Bay because of the influence of variable winds. Thus it would seem that the theory of the Ekman sprial does not apply. The relative shallowness of the basin also would seem to be an adverse factor. Because of the prevalence of shallow water and the consequent transitory thermocline development, I suspect that subsurface currents are highly influenced by surface currents and may be similar in direction to them.

Modifying factors exist in the bay to complicate the simple wind-dependent surface flow. Outflow of the streams and rivers in the area must have some effect upon surface currents. The largest of these, the Saginaw River, enters the southern end of the bay. Some of this river water must diffuse into the bay water but a discrete mass of water has been found to follow the eastern shore of the bay out into Lake Huron proper (Adams 1937). This mass well might be the flow of Saginaw River water.

A theory proposed by Steele (1957) interprets the hydrography of the northern North Sea in terms of the possible effects of lateral eddy diffusion. This diffusion depends upon the principle "that when a jet issues into a motionless fluid there is turbulent mixing along its edges making the jet gradually spread out. An important feature is that as a result of this mixing, the jet draws in fluid from its surroundings." If this theory holds true for the North Sea and other bodies of water, it may apply to Saginaw Bay also, especially if all the streams and rivers entering the bay and currents entering from Lake Huron behave as jets drawing in water laterally.

Circulation at the mouth of the bay must be affected to a large extent by movements of Lake Huron water. Harrington's (1895) work indicated that a strong current flows down the western shore of Lake Huron across the mouth of Saginaw Bay. The penetration of Lake Huron water into the bay is still a matter to be resolved through chemical and physical data collected during this study.

WATER MOVEMENTS OF LAKE HURON

Previous studies

The first account of drift-bottle work upon Lake Huron was that by Harrington (1895). He recognized a variability in surface currents of the lake when he stated, "While the winds from the Great Lakes are westerly in their prevailing direction, this is the region of variable weather, and the actual directions of the wind change from day to day. There will, consequently, be considerable variation in the currents from time to time, and this undoubtedly causes a wayward motion of the current bottles." He found that the courses taken by the bottles in Lake Huron exhibited a somewhat more complicated drift than did bottles released in Lake Superior and Lake Michigan.

Ayers (1956) adapted the oceanographers' dynamic-height method of determining currents to freshwater conditions. Findings on Lake Huron in 1954, based on this method, seemed to be in good agreement with results obtained by other methods (Ayers et al. 1956). Analysis of the data from three synoptic runs in 1954 revealed distinct differences in surface circulation at the times (spring, summer, and fall) of the runs. They concluded, further, "The fundamental surface circulation pattern in the upper and central portions of the lake appeared to be counterclockwise. In the lower end of the lake outflow to the St. Clair River appeared to consist of a meandering surface current, near or east of the midline of the lake, which approached the entrance of the river from the northeast."

Drift-bottle movements in 1956

In the present investigations, only one bottle was found below the head of the St. Clair River that flows out of Lake Huron. Of the many bottles that rounded the Michigan Thumb, most landed on the eastern side of the Thumb before reaching the river mouth. These recoveries lend some support to Ayers' contention that outflow to the St. Clair River was from the northeast.

Recoveries of 416 bottles from 760 releases along 3 transects in the southern part of the lake (fig. 4) are considered in the analysis of Lake Huron water movements. A striking feature of the returns from these releases was the scarcity of recoveries from the Saginaw Bay area (fig. 14). Only 16 bottles were found within the bay and none of these had penetrated more than 10 miles. Penetration into the bay was correlated with easterly winds during the time the bottles were adrift. As Harrington (1895) and Ayers *et al*. (1956) have indicated, however, a strong current may at times pass down the west shore of Lake Huron and set up counterclockwise rotation at the mouth of Saginaw Bay. Had bottles been released near the west shore above Au Sable Point, it is possible that many would have been carried into the bay by such a current.

The remainder of the recoveries from the Lake Huron shores were scattered widely. The tendency was marked, however, for the bottles to drift to the east (fig. 15). All recoveries from stations 2-8 were from the Michigan Thumb area, mostly on the northern and eastern sides and from the

Figure 14.--Location of 16 drift-bottle recoveries in Saginaw Bay from 760 releases on Lake Huron. Eighty bottles were released each at stations 1-6 and 40 each at stations 7-13. X's mark recovery points.

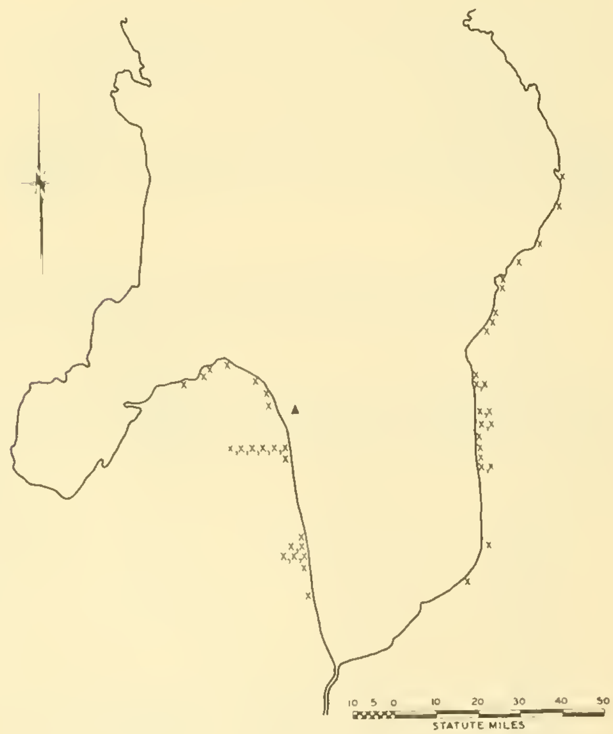


Figure 15.--Location of 45 recoveries from 80 drift-bottle releases at a Lake Huron station. Triangle marks release point; X's mark recovery points.

eastern shore of Lake Huron. All recoveries from 200 releases at stations 9-13 were from the eastern shore of Lake Huron. Apparently the surface current on Lake Huron during the summer and fall of 1956 had a net circulation from west to east.

Although the direction and intensity of local winds were important in explaining surface drift in Saginaw Bay, they appear less significant in Lake Huron proper (fig. 42 D). On August 3, 20 releases were made, 10 at each of the indicated stations, within 2 1/2 miles of one another. The large difference in direction of drift from the two stations of bottles that were out approximately the same length of time and released at nearly the same time indicates forces other than wind at work in the formation of currents.

Certainly, wind conditions play a prominent role in formations of surface currents in Lake Huron. However, the relationship between wind and currents is not nearly so obvious as in Saginaw Bay. According to Millar (1952) the energy input into a lake from a day's wind may not be completely dissipated until 12 days later. If this relation holds in Lake Huron, the prevailing winds assume a prominent role in formation of the general surface current pattern in the lake.

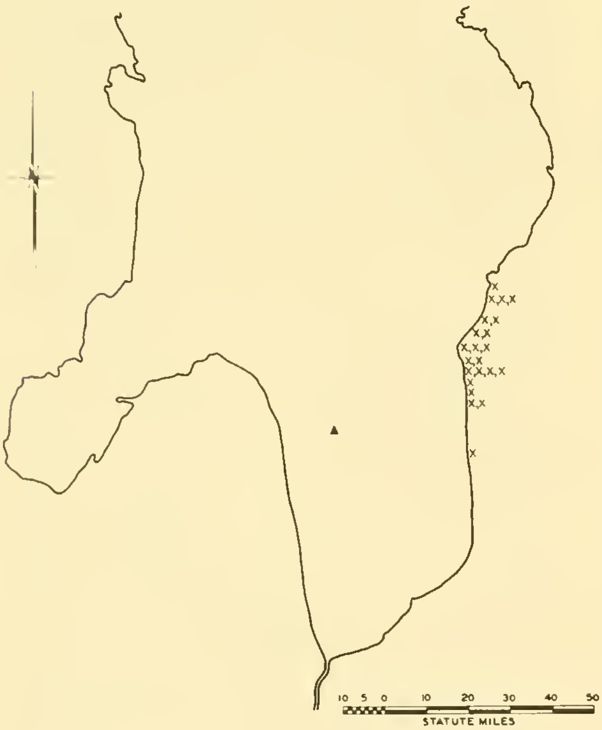


Figure 16.--Location of 22 recoveries from 40 drift-bottle releases at a Lake Huron station. Triangle marks release point; X's mark recovery points.

As was true in Saginaw Bay, location of Lake Huron returns from a particular station can vary widely throughout the season. The wide scatter of the 45 returns from 80 bottles released off Harbor Beach (10 bottles each at 8 different times from June through October 1956) is strong evidence of the instability of the lake currents (fig. 15). The drift throughout the investigation from some stations, however, could be much more stable (fig. 16).

Dynamic heights

The use of the dynamic-height method of determining current flow depends upon the availability of a subsurface reference plane at which currents are absent. Ayers et al. (1956) has indicated that Lake Huron has certain characteristics concerning circulation that are psuedo-oceanic. In calculating the relationship between wind and depth of mixing for oceans, Sverdrup, Johnson, and Fleming (1942) derived the formula $\underline{D} = 7.6 \dfrac{\underline{W}}{\sqrt{\operatorname{Sin} \varphi}}$ where $\underline{D}$ is the depth in meters, $\underline{W}$ the wind velocity in meters per second, and φ the latitude for which the calculation is made. If 44° (the approximate average latitude for southern Lake Huron) is substituted for φ and 6.7 meters per second (a common wind velocity over Lake Huron during the summer) is substituted for $\underline{W}$, $\underline{D}$, or the depth of the layer that is stirred up by wind becomes approximately 60 meters. Mortimer (1954) believed that mixing (water movement or currents) may occur in some lakes to depths three times that of the thermocline. The average depth of the thermocline in south-central Lake Huron during the summer of 1956 was 50 feet. In order to lessen the probability of currents below the base, a depth of 60 meters (somewhat more than 3 times the 50-foot level of the thermocline) was taken as a reference plane for dynamic-height calculations.

Use of this method to determine currents was limited because records were available from only one transect for any one day. For best results a large number of stations over an area should be available so that dynamic-height contours can be drawn with the minimum of uncertainty. The dynamic heights at points along the transect gave only an approximation of the initial direction of flow of current. For instance, if the dynamic heights indicated a northerly component, current flow could actually be northeast, northwest, or even a mere fraction of a degree north of east or west. The use of this method in conjunction with drift bottles was of some value in determining possible surface-current flow in the lake (figs. 17 A-D, see page 20). This analysis indicates that surface-current patterns may be much more complicated than has been realized.

The dynamic-height method in surface-current calculations might not be applicable in and around the littoral zone. On two occasions off Canadian shores, August 3, 1956 (fig. 17 B), and October 27, 1956 (fig. 17 D), calculations indicated currents near shore to be to the south but bottles released in the area on these dates drifted to the north. The possibility exists, however, that the bottles at first drifted to the south but later their direction of drift was reversed.

The rate of change in the dynamic heights is still a matter of conjecture. Prominent changes over a period of approximately 5 weeks resulted in new current patterns as shown by figure 17 (A-D). Variation from one day to the next was so small that no significant change in current pattern resulted (table 6). Over a period of days, however, the total of these small differences produced the prominent changes noted between cruises.

What effect internal waves in the Great Lakes have upon the geopotential topography should be resolved. According to Sverdrup, Johnson, and Fleming (1942), "...charts of geopotential topography may not represent the average topography of the free surface but may show a number of features which, instead of being associated with the general distribution of mass, are brought about by the presence of internal waves. In view of this circumstance which, so far, has not received great attention, conclusions as to general currents based on charts of geopotential topography should be used with even more reservation than has been previously emphasized." However, in support of the dynamic-height method of determining currents they remark that, "So many reservations have been made that it may appear as if the computed currents have little or no relation to the actual currents. Fortunately, however, most of the assumptions made lead only to minor errors, and currents can be correctly represented in the first approximation by means of the slopes of a series of isobaric surfaces relative to one reference surface."

Appraisal of the general pattern

Although no one characteristic current system is indicated for Lake Huron, the following general remarks concerning surface circulation in Lake Huron in 1956 seem pertinent: There is a general but highly variable west-to-east drift; the most highly developed west-to-east drift occurs during August and September; there is some inflow

Table 6.--Dynamic heights in meters (reference level 60 meters) for stations on the Harbor Beach, Michigan-Goderich, Ontario, transect on successive days during three months of 1956

Statute miles from Harbor Beach	Date					
	June 22	June 23	August 3	August 4	September 15	September 16
3.0	59.992	59.995	60.016	...	60.030	...
5.0	59.996	...	60.018	...	60.032	...
7.0	59.998	59.998	60.019	60.027	60.033	60.025
12.0	60.003	60.008	60.022	...	60.034	60.034
17.0	59.996	60.000	60.020	...	60.034	60.034
22.0	59.999	60.000	60.018	...	60.026	60.029
27.5	59.992	59.995	60.028	60.024	60.033	60.033
32.5	59.994	59.996	60.021	60.018	60.033	60.033
37.0	59.999	59.997	60.012	60.005	60.028	60.027
41.5	60.000	60.005	60.005	60.006	60.021	60.018
44.0	60.004	60.005	59.998	60.002	60.020	60.018

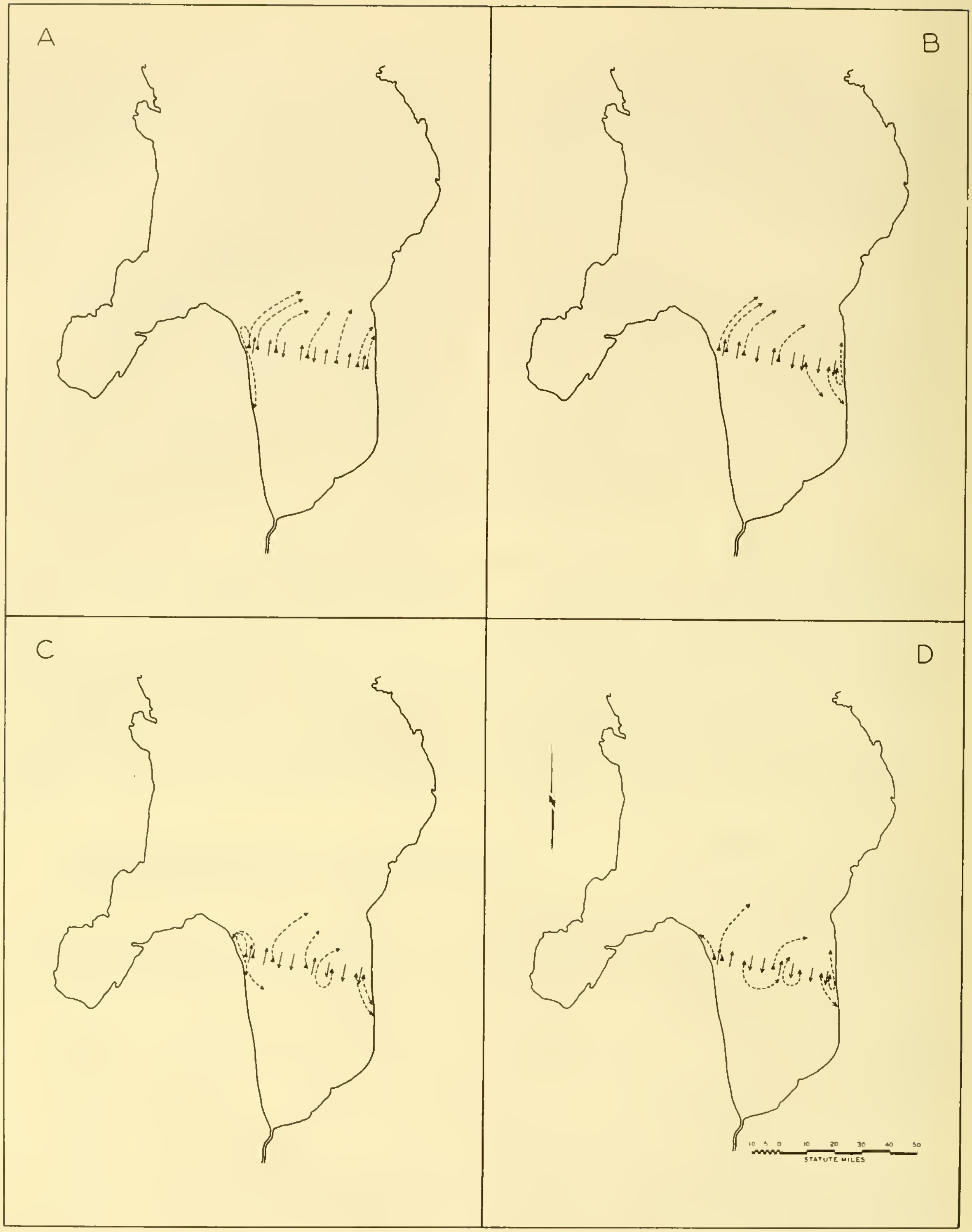


Figure 17.--Surface-current flow in Lake Huron determined from dynamic heights (solid lines) and drift-bottle movements (broken lines). Dynamic heights calculated and drift bottles released on June 22, 1956 (A), August 3, 1956 (B), September 15, 1956 (C), and October 27, 1956 (D).

of surface water into Saginaw Bay; a strong southerly littoral current flows at times along the eastern coast of the Michigan Thumb area (figs. 18 A-C, see page 22).

RATE OF DRIFT

Reliability in computing rate of drift of bottles is impaired by a lack of knowledge of how long a bottle was ashore before it was discovered, and by a lack of information on the course a bottle followed from its release point to the recovery point. Effects of the first of these two factors might be minimized by using in calculations only those bottles that are actually observed washing ashore or those found still drifting in the water. However, comparisons of records for bottles from the same lot that traveled similar courses revealed that many discovered still floating or washing ashore exhibited a lower rate of drift than those recovered from the shore. Most probably some of the former had actually been beached and refloated by changes in winds, water level, and wave actions. For this reason computations of rate of drift were not restricted to recoveries of bottles found still floating or washing ashore.

The second factor, lack of any means of determining the exact course of a bottle from its release point to its recovery point, is not to be eliminated. The straight-line distance from release point to recovery point has been used in calculating the rate of transport.

A bottle exhibiting a high rate of drift along a course should be a better indicator of the actual drift rate than the average of the rates of all of the bottles traveling this course. The average rate might include bottles that were on the shore many days before they were found. The average drift rate can be of value, however, not in indicating actual speed, but in making certain comparisons between cruises (table 7).

During and for a short time after Cruise I in June 1956, winds were variable but they did display some tendency to be from the west. Six bottles of 110 dropped at the mouth of Saginaw Bay crossed the lake east to the Canadian shore at a minimum average rate of 0.95 miles per day, the lowest averate rate of bottles that crossed the lake for all the cruises (table 7). The average rate of movement increased for bottles that were released at the mouth of Saginaw Bay on Cruises II and III and later recovered in Canada. During Cruise II, however, only one bottle made this crossing--not enough to give a fair value for this cruise. The number of bottles crossing the lake that were released during Cruises IV and V was more than twice the number that crossed from releases of the six other cruises. During August and the first weeks of September when bottles released on Cruises IV and V were adrift, the prevalence of westerly winds was greater than at any other time during the investigations. Recovery of bottles from Cruises VI, VII, and VIII that crossed the lake was low and no trend is apparent in the average drift rate. Coverage of shore area and consequently returns from these last cruises were much lower than for the earlier ones. Had better coverage existed, perhaps, more bottles would have been found on the Canadian shores.

Rapidly moving bottles, those drifting at an arbitrarily chosen 3 miles per day and faster (10 percent of the bottles recovered) have been used to give some indication of actual drift rates approached along assumed straight-line courses (figs. 18 A-H, see pages 22 and 23). The large number of rapidly drifting bottles recovered

Table 7.--Number of bottles released at stations at the mouth of Saginaw Bay each cruise in 1956, total number of recoveries of these bottles crossing Lake Huron, and the average minimum rate of drift bottles made in the crossing

Cruise	Dates of release	Number of bottles released	Number of bottles recovered that crossed to Canada	Average minimum rate of drift in miles per day
I	June 5-7	110	6	0.95
II	June 21-29	110	1	1.73
III	July 13-18	110	19	1.89
IV	August 2-10	110	51	1.95
V	August 24-30	110	34	2.35
VI	September 13-21	110	7	2.07
VII	October 5-12	110	0	...
VIII	October 27-30	110	3	2.07

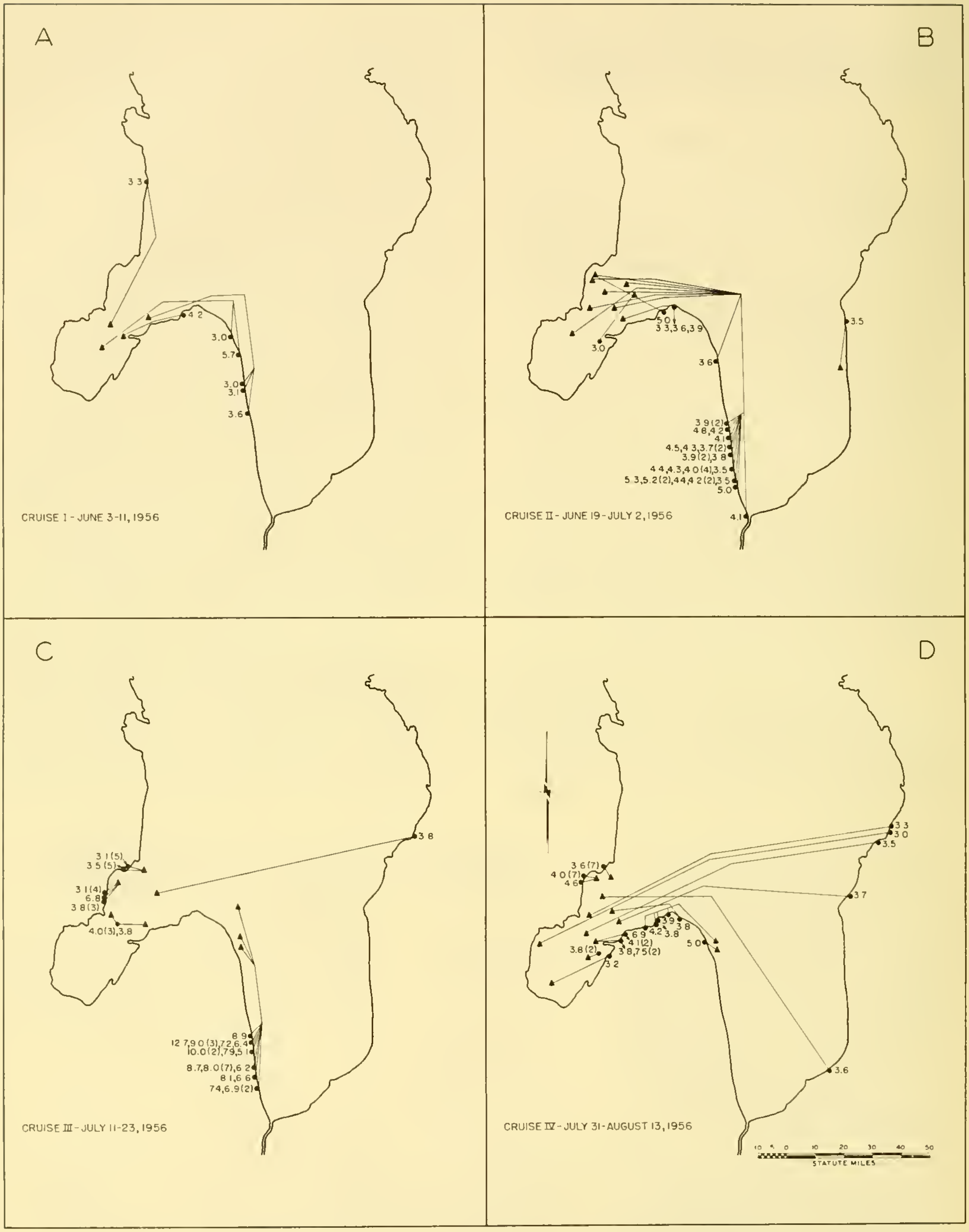
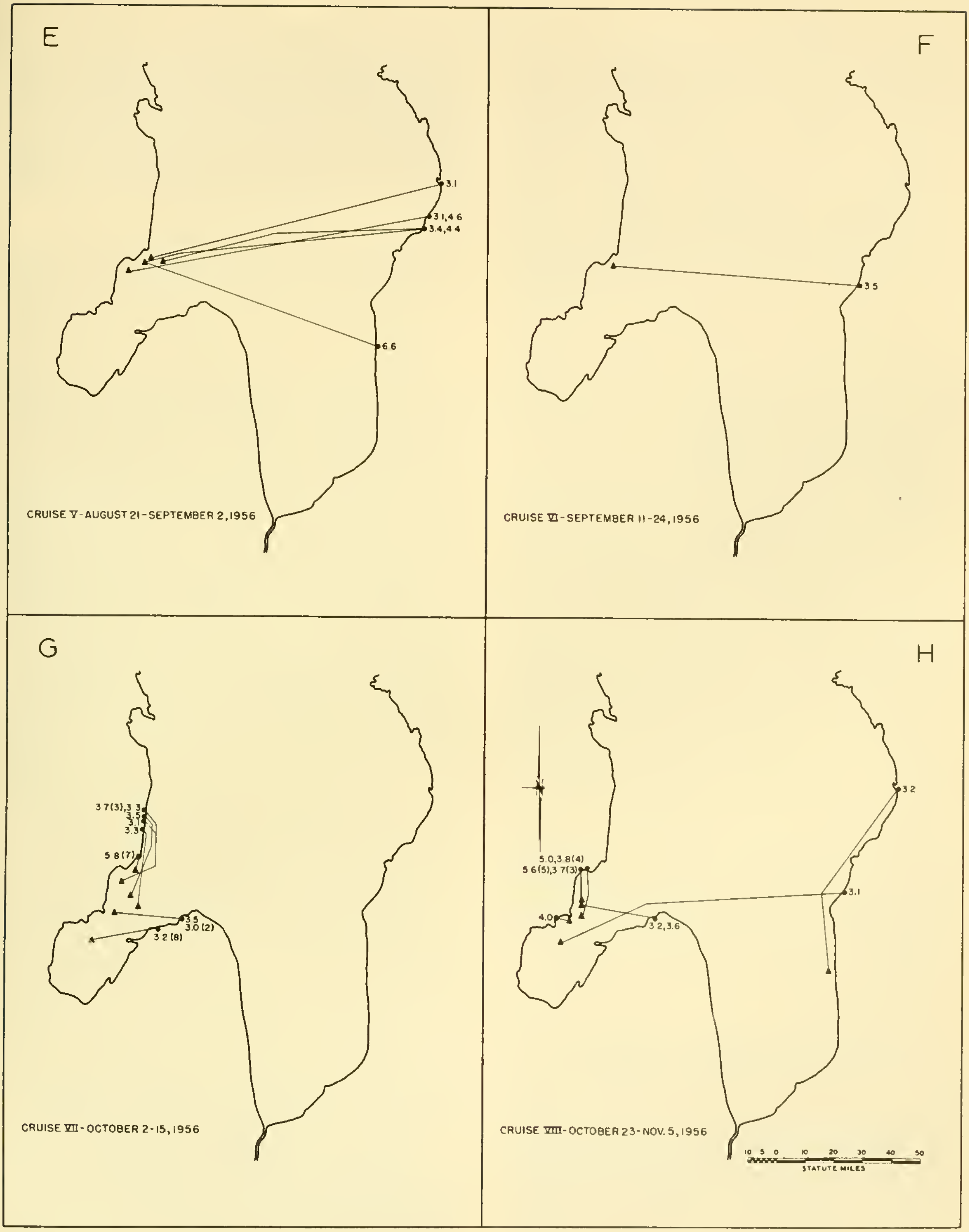


Figure 18.--Release, recovery points, and tracks of bottles traveling at least 3 miles per day along straight-line courses. Triangles show release points. Drift rate indicated by



number to the nearest tenth of a mile per day. Whole numbers in parenthesis show number of bottles traveling at indicated rate.

from the releases on Cruises I, II, and III consistently show a strong current down the eastern shore of the Michigan Thumb (figs. 18 A-C); rates were as high as 12.7 miles per day for bottles released on Cruise III. During and for a short period after these cruises in June and July 1956, the winds over the lake were largely from the north and the west. A temporary reversal of the strong surface current clockwise around the tip of the Michigan Thumb is indicated by the travel of bottles released during Cruise IV (fig. 18 D). Apparently this reversal was caused by strong east winds that blew during the first week of August. Of the bottles released on Cruise IV (fig. 18 D) and V (fig. 18 E), the general direction of those moving 3 miles per day and faster was to the east. This easterly drift coincided with prevailing westerly winds during August and September 1956. Of the bottles released on Cruises VI, VII, and VIII (figs. 18 F-H) only two crossed to the Canadian shore at a rate in excess of 3 miles per day. The remainder of the "rapid drifters" traveled to the north (figs. 18 G-H). During the time that these bottles were adrift, the prevailing winds were from the south.

It might seem that the bottles that had lost their drags would predominate in those classed as "rapid drifters". Without drags bottles presumably come more under the direct influence of wind. However, of the 168 bottles of these studies that drifted at a rate of 3 miles per day or better, only 9 had lost their drags.

It should not be assumed from these remarks and figures that no speeds of drift greater than those given were attained. Also, most certainly other bottles would be included as "rapid drifters" if the exact tracks of the bottles as well as their exact landing times were known.

QUANTITATIVE RELATIONSHIP BETWEEN SURFACE DRIFT AND WIND

Garstang (1898) believed the relationship between winds and surface currents were so precise that he worked out a quantitative relationship between the two. He developed the formula $\underline{D} = \frac{5\ \underline{Pn}}{2\underline{n}}$ where $\underline{D}$ is the distance traveled in miles and $\underline{Pn}$ is the resultant pressure in pounds per foot determined from $\underline{n}$ observations daily. The accuracy of this method depends on the assumption that the velocity of drift varies as the pressure of the wind and not directly as its velocity. Pressures were obtained from the following set of values:

Force, Beaufort scale	0	1	2	3	4	5	6	7	8	9	10	11	12
Velocity, miles per hour	3	8	13	18	23	28	34	40	48	56	65	75	90
Pressure, pounds foot	0.05	0.3	0.8	1.5	2.5	4	6	8	11.5	15	21	28	40

Pressure-equivalents were computed from the velocities by multiplying the squares of the velocities by the factor 0.005 and expressing the results in whole numbers. Garstang did not give proof that these computations were valid but remarked that the table had been authorized by the Meterological Office in 1875. He admitted that the pressure-ratio is only an approximation to the true law of drift. However, his calculated and empirical travels of drift bottles were fairly close. But he wrote, "Some further examination, however, is necessary before the reliability of my method can be depended upon, because the estimated results depend upon the assumption of open water, and this cannot always be conceded."

R. Witting (Carruthers 1927) decided that the formula, $\underline{V} = \underline{MW}^{1/2}$, could be used to show wind-surface drift relationship where $\underline{V}$ is the velocity of drift in centimeters per second, $\underline{W}$ is wind speed in centimeters per second, and $\underline{M}$ is a constant. In observations at Finnish lightships, Witting computed the value of $\underline{M}$ to be 0.44; the equation then became $\underline{V} = 0.44\underline{W}^{1/2}$. Carruthers in using the same formula with $\underline{V}$ and $\underline{W}$ expressed in miles per day, arrived at an $\underline{M}$ value of 0.45 for the English Channel. Daniel and Lewis (1930) in work on the Irish Sea, expressing $\underline{V}$ and $\underline{W}$ in miles per day, arrived at values of $\underline{M}$ from .04 to 1.29 for different sectors. In later work on the English Channel, Carruthers (1930) worked out the formula $\underline{S} = 1/18\ \underline{W}$ for the wind-surface drift relationship where $\underline{S}$ is bottle travel in miles per day and $\underline{W}$ the wind speed in the same units. Days of similar wind conditions, with little day-to-day variation, enabled him to work out this relationship. He was quick to point out, however, that this relationship was not necessarily applicable to waters other thantthose he studied. He inferred that it would be foolish to seek any equation other than a simple one because of the many variables involved.

Welch (1952) wrote that in large lakes such as the Great Lakes surface velocity is claimed to be about 5 percent of that of the wind causing it but that the percentage was less than 5 in smaller lakes. This statement is in agreement generally with Stromsten (1929) who found that a wind of 800 feet per minute produced a surface current of 25 feet per minute on Lake Okoboji, Iowa. Expressed in percentages, the surface current there was about 3 percent of the wind velocity. According to Whipple (1927), Ackermann found the surface current to be 3 percent of a wind velocity of 5 miles per hour and 1 percent of a wind velocity of 30 miles per hour on Owasco Lake, New York. Velocity at a depth of 10 feet was about 60 percent of the surface velocity and at 20 feet it was 25 percent.

In this study no attempt has been made to correlate quantitatively wind velocity and surface drift. To do so accurately would require knowledge of the characteristics of reasonable steady winds from any one direction, knowledge of the exact time of bottle travel, and an accurate track of the bottle drift. At no time could we be certain of the true course of bottle drift. It was seldom that wind velocity remained fairly stable for several days after the releases and occasions when bottles were actually seen to land were rare. At no time did the two conditions, necessary for accurate computation, exist simultaneously. When steady wind conditions did prevail for several days, no bottles were seen to land that had completed their entire travels under this wind.

Another major difficulty in determining the relationship between water current and wind velocity in regions of variable winds is the lack of information on the exact rate at which surface currents adjust to a changing wind. Once this problem is solved, we shall be in a better position to compute the relationship quantitatively.

FACTORS INFLUENCING DRIFT-BOTTLE MOVEMENTS

Surface currents in Saginaw Bay and Lake Huron are extremely variable and are dependent largely upon wind conditions. However, the effects of winds on the two bodies of water differ to a large extent because of dissimilar morphometry of the basins. Saginaw Bay is shallow, long, and narrow, whereas Lake Huron is much deeper and larger.

Saginaw Bay

In Saginaw Bay changes in the local winds will alter surface currents in a very short time as the energy accumulation in currents in Saginaw Bay is far below that of currents in Lake Huron. Because the surface currents in the bay are so dependent upon local winds, any pattern described should be related to the winds producing it if results are to be meaningful.

Forces other than winds which modify the surface currents in the bay result from inflows of streams and rivers and possibly ground water. Lake Huron water also alters current patterns as it enters or leaves the bay. Lake Huron water enters principally along the western area of the bay.

The shoreline in the lower reaches of the bay, especially the eastern, is ill-defined. Extensive areas in this region are covered with emergent aquatic vegetation. It is apparent that currents in this portion of the bay are relatively moderate. However, it was here that direction of wind and direction of bottle travel were most closely correlated.

Shore areas in the outer half of the bay indicate much stronger eroding action from currents. Although surface currents flowed outward at some time at different points at the mouth of the bay, the principal outflow was along the eastern shore and thence around the tip of the Michigan Thumb area. The correlation between wind direction and direction of bottle drift in the outer half of the bay broke down at times, most likely because of the influence of the currents entering from Lake Huron. A general counterclockwise circulation with inflow along the western shores and outflow along the eastern shores was observed several times during the summer and fall.

Lake Huron

In Lake Huron the prevailing winds are more important than local winds in forming current patterns. The energy input into the lake by the prevailing wind is not dissipated by temporary wind shifts. Currents on any one day reflect the wind input of the previous days (at least 12, according to Millar 1952). The general drift in Lake Huron was from west to east; it was caused presumably by the prevailing westerly winds. This finding seems to support Millar's theory. On the other hand, bottles under the influence of strong local winds moved, at times, against the prevailing pattern. The most marked of these exceptions to pattern was the drift of bottles from east to west around the tip of the Michigan Thumb area where there is normally a strong current in the opposite direction. Other examples of this reversal against the prevailing pattern were noted in the Tawas Point-Au Sable Point area. Millar's statement to the effect that the energy input is not dissipated for several days might not apply to the surface water; at least it would seem not to apply in the above-cited reversals.

The effects of stratification upon currents present an unsolved problem in Lake Huron. The depth to which currents are present in stratified lakes is still a subject of much study. As Mortimer (1954) has found, subsurface currents are, most likely, present in water much deeper than was formerly realized and, consequently, are of some significance.

Ayers' (1956) method of using dynamic heights has contributed a new concept in calculating surface currents of large inland lakes. But as he has suggested, this method should always be checked by means of other parameters to determine whether it is giving valid results. His method may be limited in some degree by the high ratio of shoreline to surface-water area and the confined nature of some areas of inland basins. The shoreline, if appears, plays an important role in conforming currents into some pattern regardless of the dynamic heights. Dynamic-height calculations indicate that in open waters surface currents also are variable. Apparently, movement of water from west to east in Lake Huron does not follow a straight line, but direction changes several times before it reaches the Canadian shores.

RECOMMENDATIONS FOR STUDY OF CURRENTS ON THE GREAT LAKES

Current-pattern determination on the Great Lakes is still in its earliest state of development. The few studies available leave much to be desired. Just what the subsurface currents are and what their relation to surface currents is remains a matter of conjecture. Surface-current observations have not extended over long enough periods to support conclusions regarding seasonal patterns. If the true nature of currents in the Great Lakes is to be determined, a program must be carried out that will include the following points:

1. Study one lake or one area of a lake for a period of several years throughout all seasons. Such a project should disclose what forces are at work in formation of currents, and thus lay the foundation for predictions of currents.

2. Employ various methods in determining currents and check each method against others and against known conditions whenever possible. The reliability of each method could be ascertained and the limitations of each determined.

3. Study the degree of correlation between meteorological conditions and current patterns. Present methods of recording wind data over the lake should be refined. Recent evidence indicates that large variations in the winds occur.

4. Develop new equipment and methods and use devices other than drift bottles. The transponding drift buoy as described by Bumpus *et al.* (1957) appears to hold much promise as a current indicator. The tracking of radio signals emitted from this free floating buoy makes it possible to determine its movement precisely. Investigate the use of the radioactive isotope as an aid in determining movements of water masses. Recently, the City of Los Angeles employed isotopes to determine the path of the flow of sewage into the Pacific Ocean.

Although the use of isotopes is expensive, it is believed that in the near future the cost will decrease greatly.

5. Investigate littoral currents more thoroughly and determine the relationship between lake morphometry and currents.

6. Undertake the determination of subsurface currents and the relationship between subsurface and surface currents.

Costs of such a program would be high both in money and time. It will, however, be necessary if the true nature of currents is to be found and predictions of currents made possible.

ACKNOWLEDGMENTS

The following agencies and individuals contributed to this study: the crews of the U. S. Fish and Wildlife Service research vessels Cisco and Musky assembled and released drift bottles; the crews of the Michigan Department of Conservation Patrol Boats Nos. 2 and 3 assisted in releasing drift bottles; the U. S. Coast Guard made wind records available; many, many persons returned the cards from the bottles; Mr. William Cristanelli drafted the figures; James Moffett, Ralph Hile, and Stanford Smith of the Great Lakes Fishery Investigations and John Ayers of the Great Lakes Research Institute made suggestions in the preparation of this manuscript.

SUMMARY

1. The U. S. Fish and Wildlife Service and the Michigan Department of Conservation, in a cooperative project, conducted a comprehensive limnological survey in Saginaw Bay and adjacent Lake Huron waters in the summer and fall of 1956. As a part of this project in order to gain information on surface currents, drift bottles were used in Saginaw Bay, and drift bottles together with the dynamic-height method were used in lower Lake Huron area.

2. The drift bottle consisted of a 4-ounce Boston round bottle corked, sealed with beeswax, and fitted with a metal drag suspended 12 inches below the neck of the bottle by a piece of black iron wire. The purpose of the drag was to reduce the direct influence of the wind upon bottle movement. For the most part drags appeared to function properly up to at least 30 days, after which time many broke away from their drift bottles.

3. A total of 2,650 of these units were released from the U. S. Fish and Wildlife Service research vessels Cisco and Musky and Michigan Department of Conservation Patrol Boats Nos. 2 and 3. Subsequently 1,843 (69.5 percent) reply cards from the recovered bottles were returned. Of these, 240 were returned after the cut-off date of February 28, 1957, and were not used in studies of surface currents.

4. Recovery of bottles during the summer and fall was greatest over weekends with this becoming more pronounced after August. Percentage return of bottles released from any one of the nine cruise periods decreased as the season progressed.

5. Wind records at the Tawas Point, Bay City, and Harbor Beach, Michigan Coast Guard stations were used in drafting wind tracks.

6. There appeared to be a high correlation in Saginaw Bay between direction of surface currents that moved these bottles and direction of winds. In Lake Huron this correlation applied to a lesser extent although the drift of bottles was generally from west to east, apparently under the influence of the prevailing westerly winds of this area.

7. Use of the dynamic-height method in Lake Huron was restricted because of the paucity of stations covered. It appeared, however, from results using this method along with drift bottles that the surface currents in Lake Huron are much more complicated than has been suspected.

8. Greatest rates of drift were obtained from bottles drifting clockwise around the top of the Michigan Thumb, thence south along the east coast of the Thumb.

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APPENDIX

Figures 19-27 contain the release and recovery points of drift bottles floated in the 1956 Saginaw Bay-Lake Huron study. Meanings of numbers and symbols used are as follows:

1. Triangle - release point.
2. Dot - recovery point.
3. Plain number - number of days between release and recovery. Drift unit intact.
4. Number circled - same as No. 3 except unit without drag when recovered.
5. Number enclosed by square or rectangle - same as No. 3 except loss or retention of drag not indicated.
6. Number enclosed by hexagon - same as No. 3 except reply card only was found.
7. Question mark - number of days between release and recovery not known.

A bottle recovered on the day it was released was considered to have been adrift zero days. If it was recovered the day after release, the drift period was one day.

The wind track from the Coast Guard station nearest the drift paths of the bottles is included on each page. The wind track includes the wind vectors 4-10 days prior to release of bottles as well as the time interval during which the wind might be influencing bottle movement. Numbers on the wind track are dates and indicate the end of a 24-hour period.

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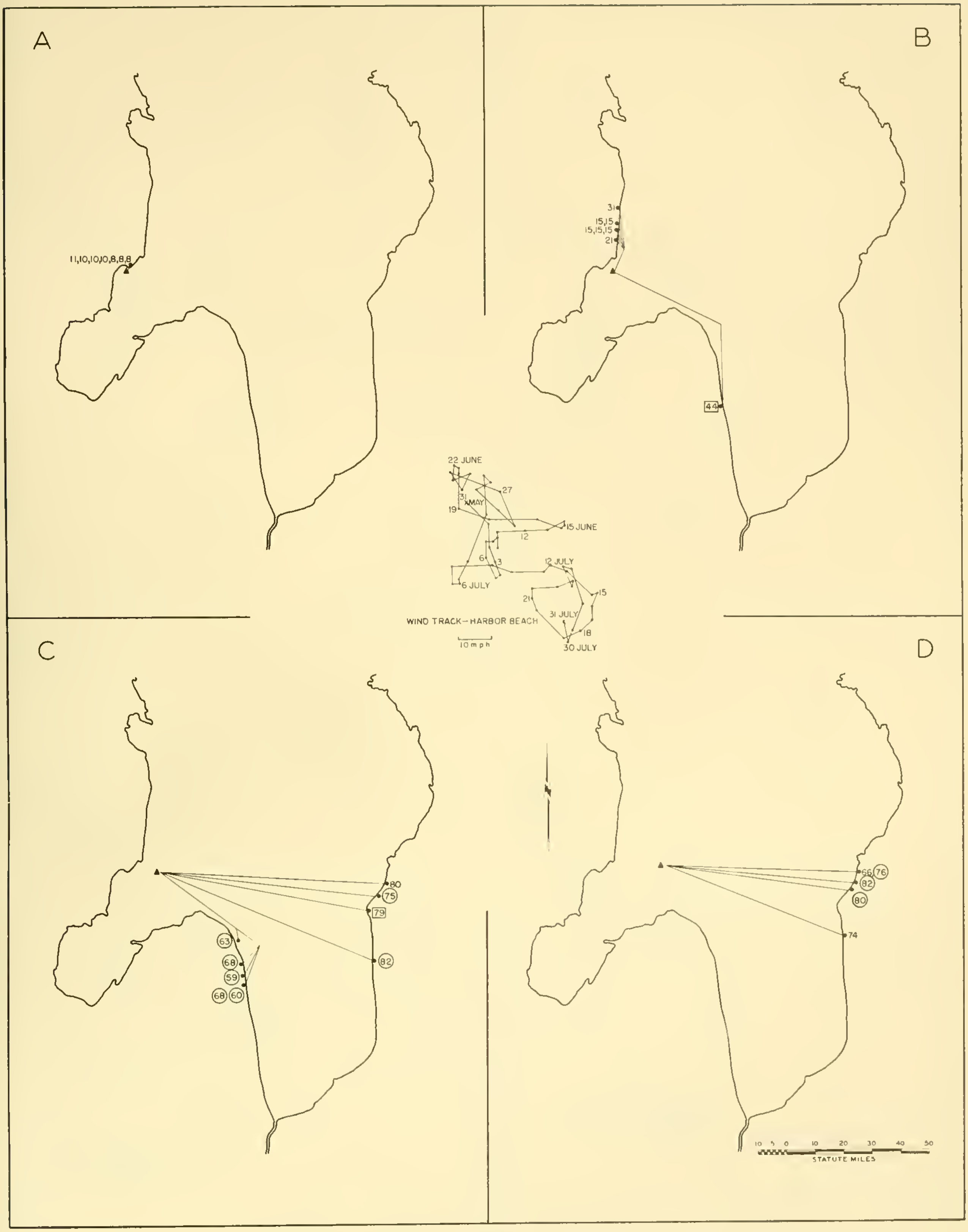

Figure 19.--Recovery points of drift bottles released June 5, 1956.

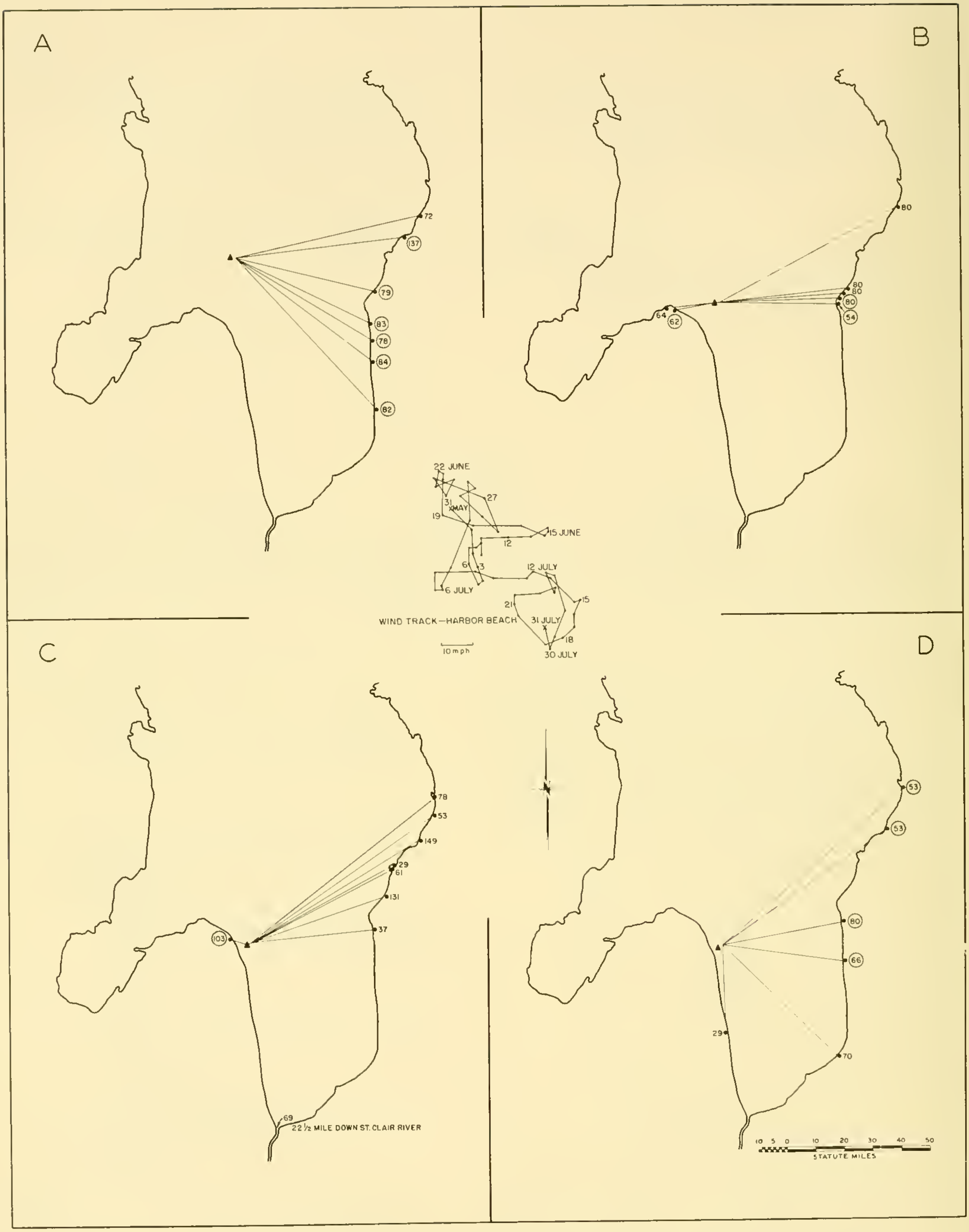

Figure 20.--Recovery points of drift bottles released June 5, 1956.

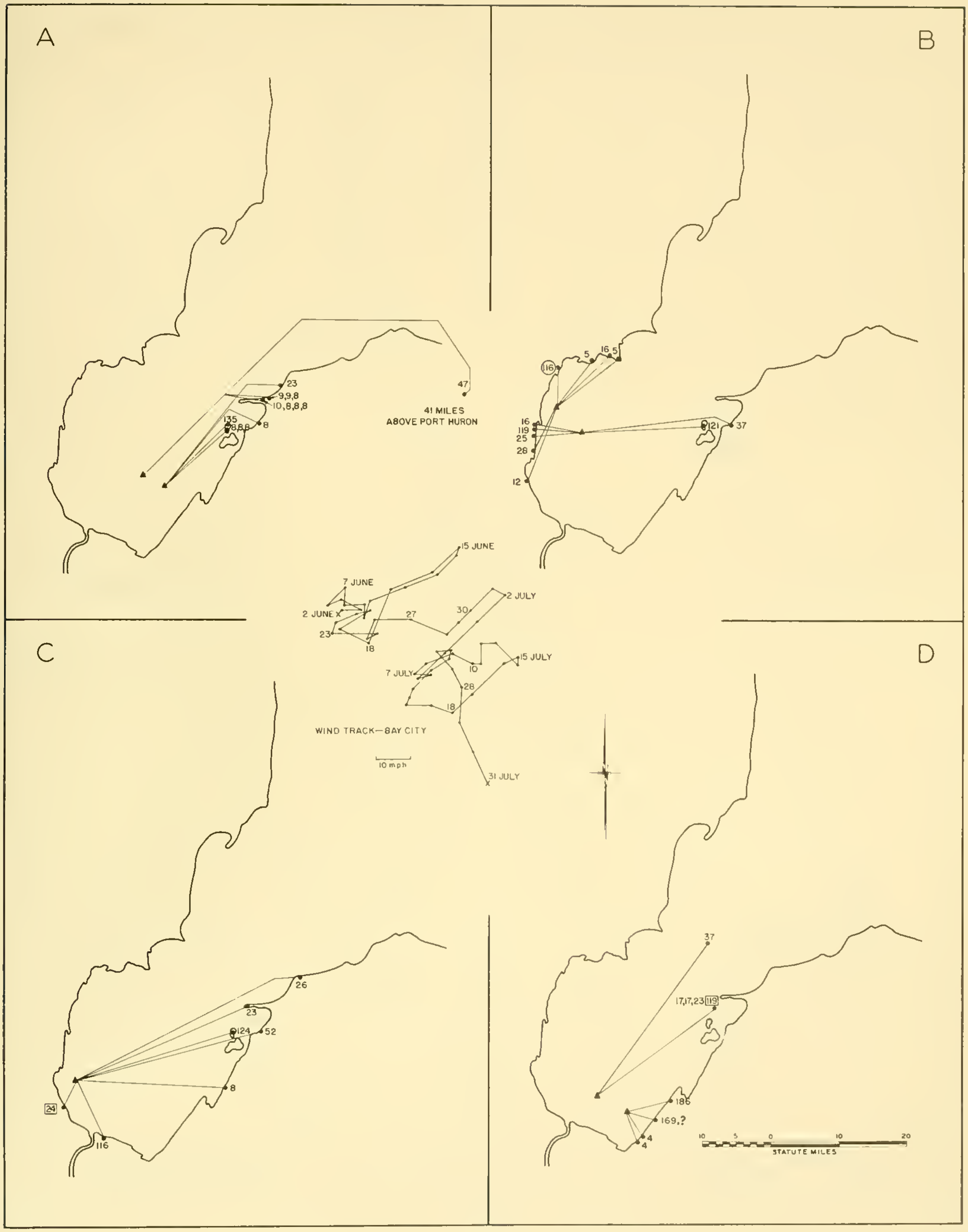

Figure 21.--Recovery points of drift bottles released June 7, 1956.

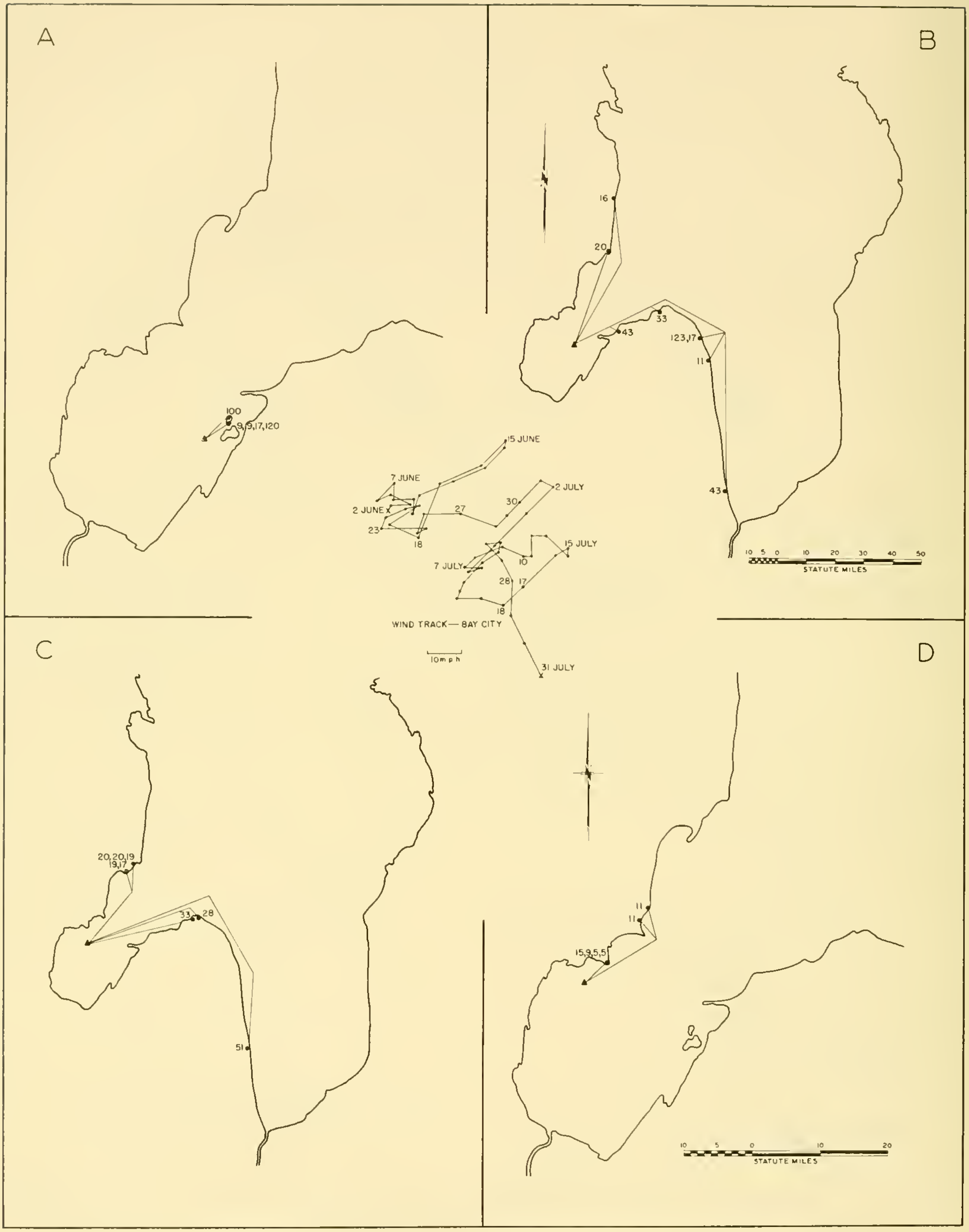

Figure 22.--Recovery points of drift bottles released June 7, 1956.

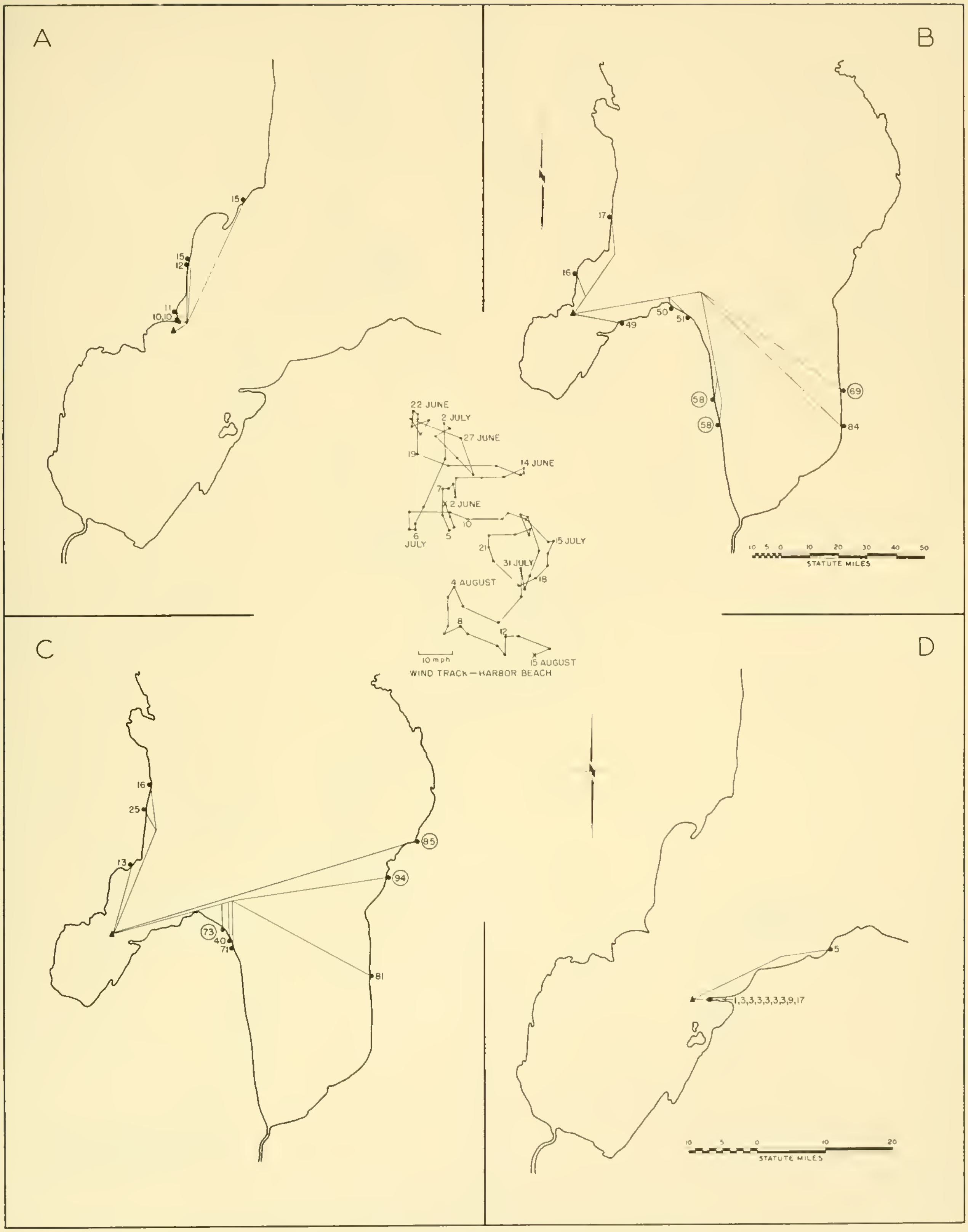

Figure 23.--Recovery points of drift bottles released June 7, 1956.

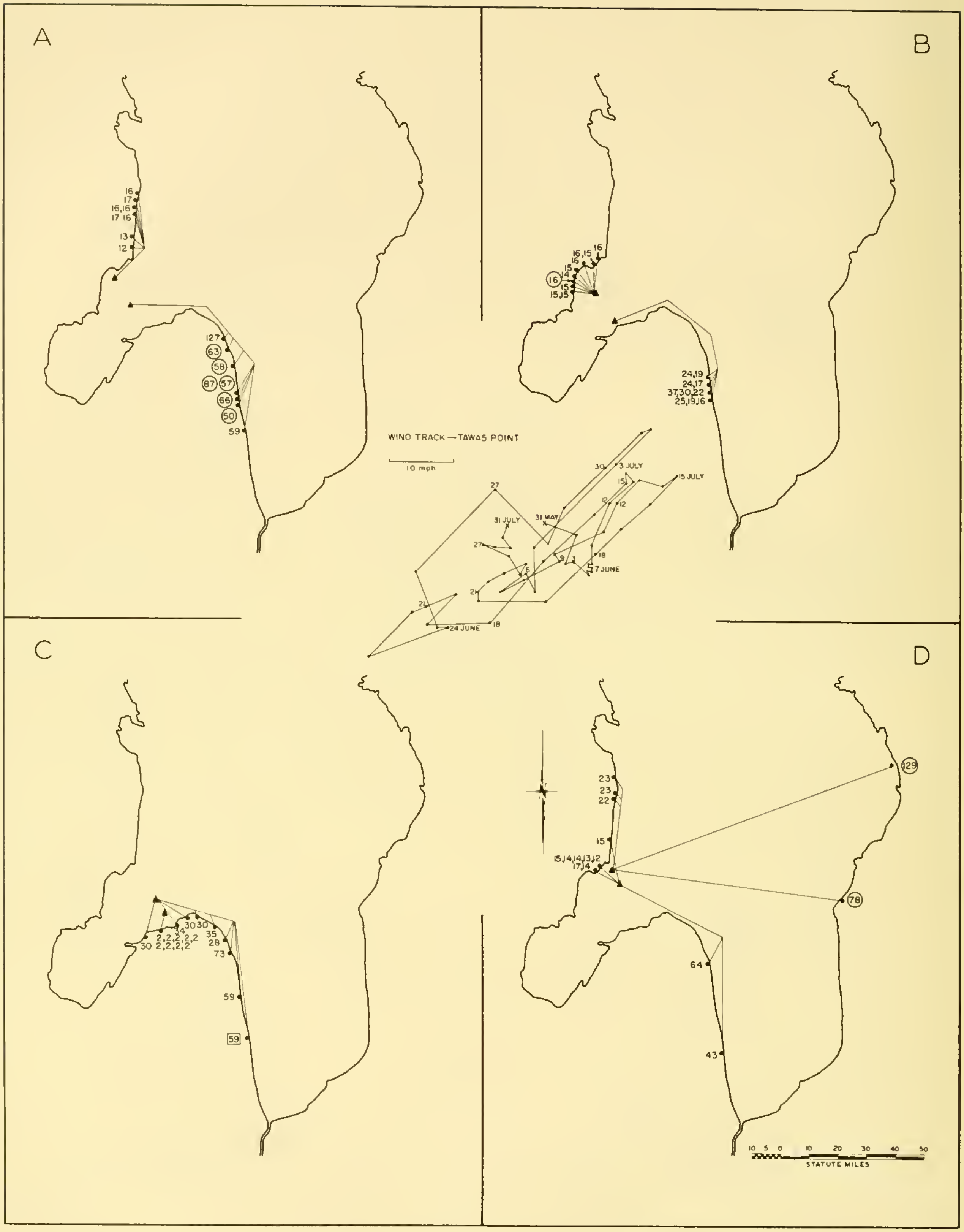

Figure 24.--Recovery points of drift bottles released June 7, 1956.

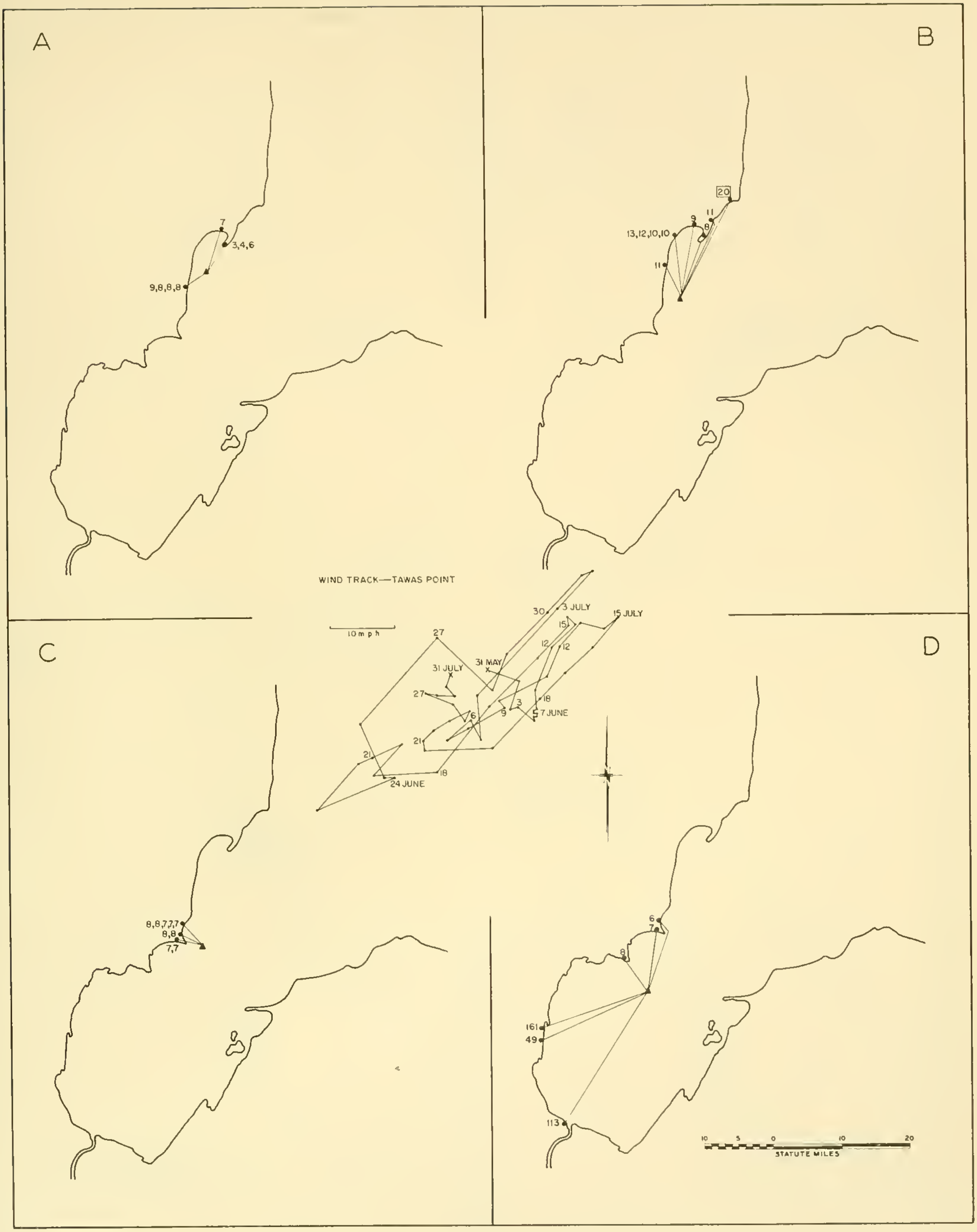

Figure 25.--Recovery points of drift bottles released June 10, 1956.

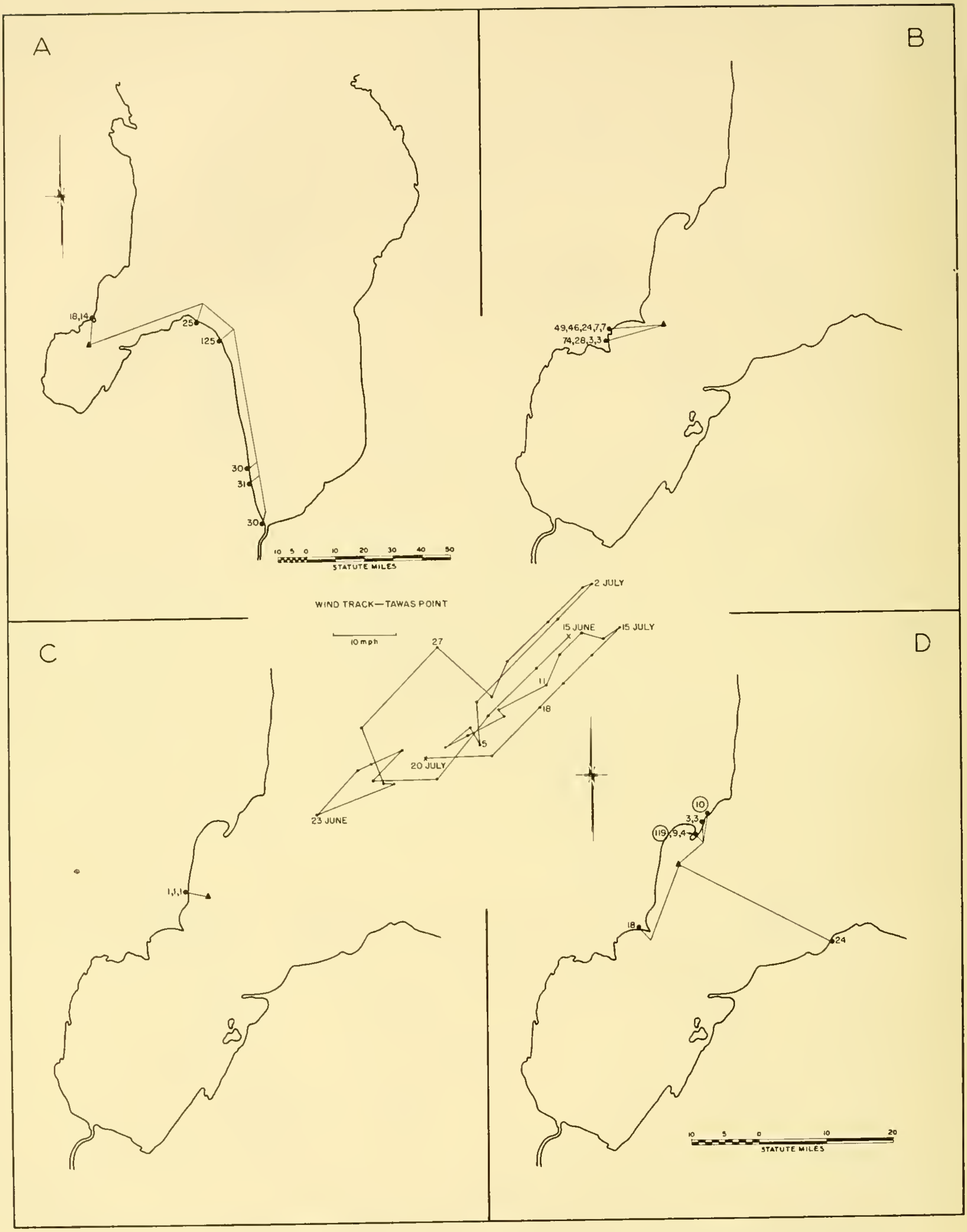

Figure 26.--Recovery points of drift bottles released June 20, 1956.

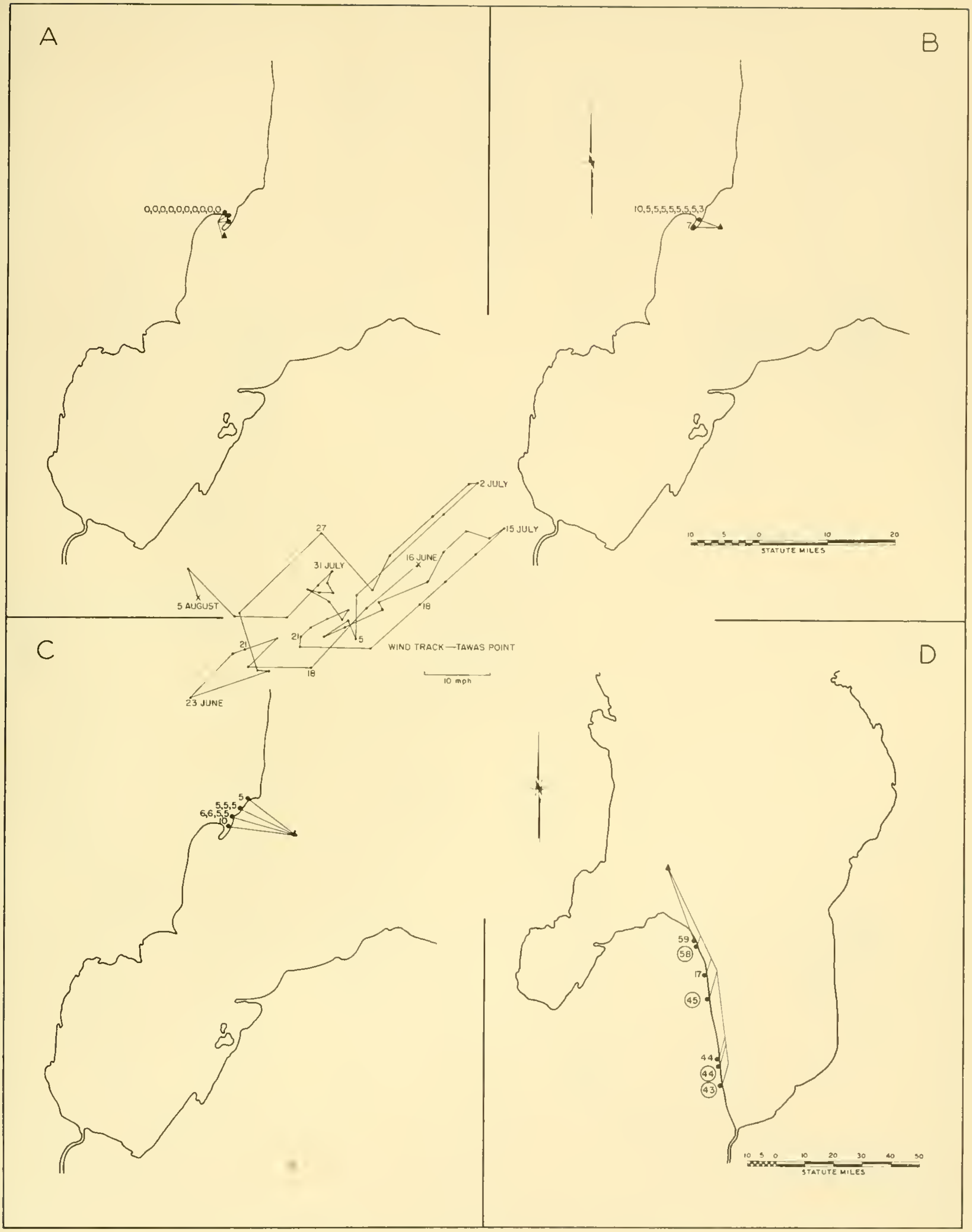

Figure 27.--Recovery points of drift bottles released June 21, 1956.

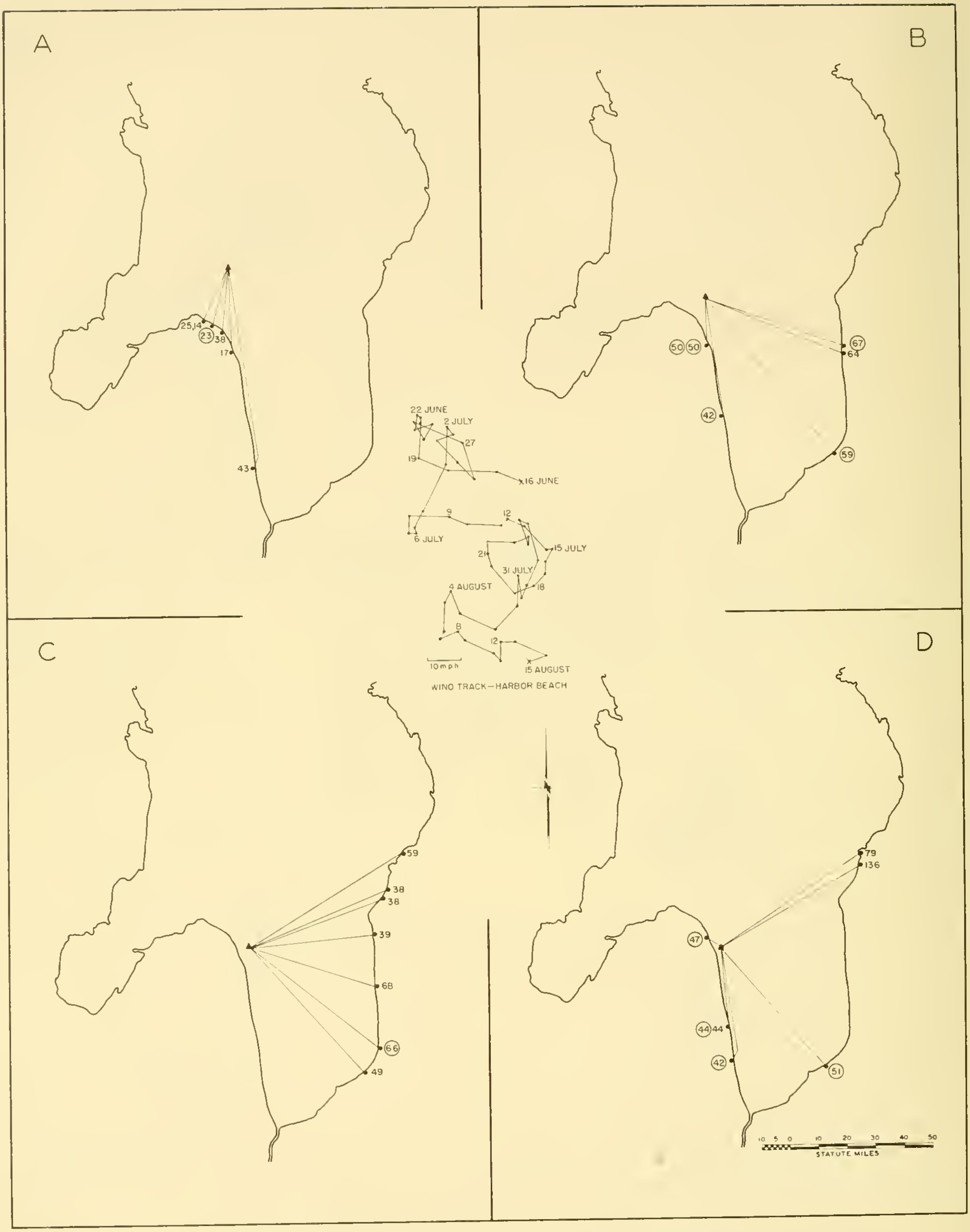

Figure 28.--Recovery points of drift bottles released June 21, 1956.

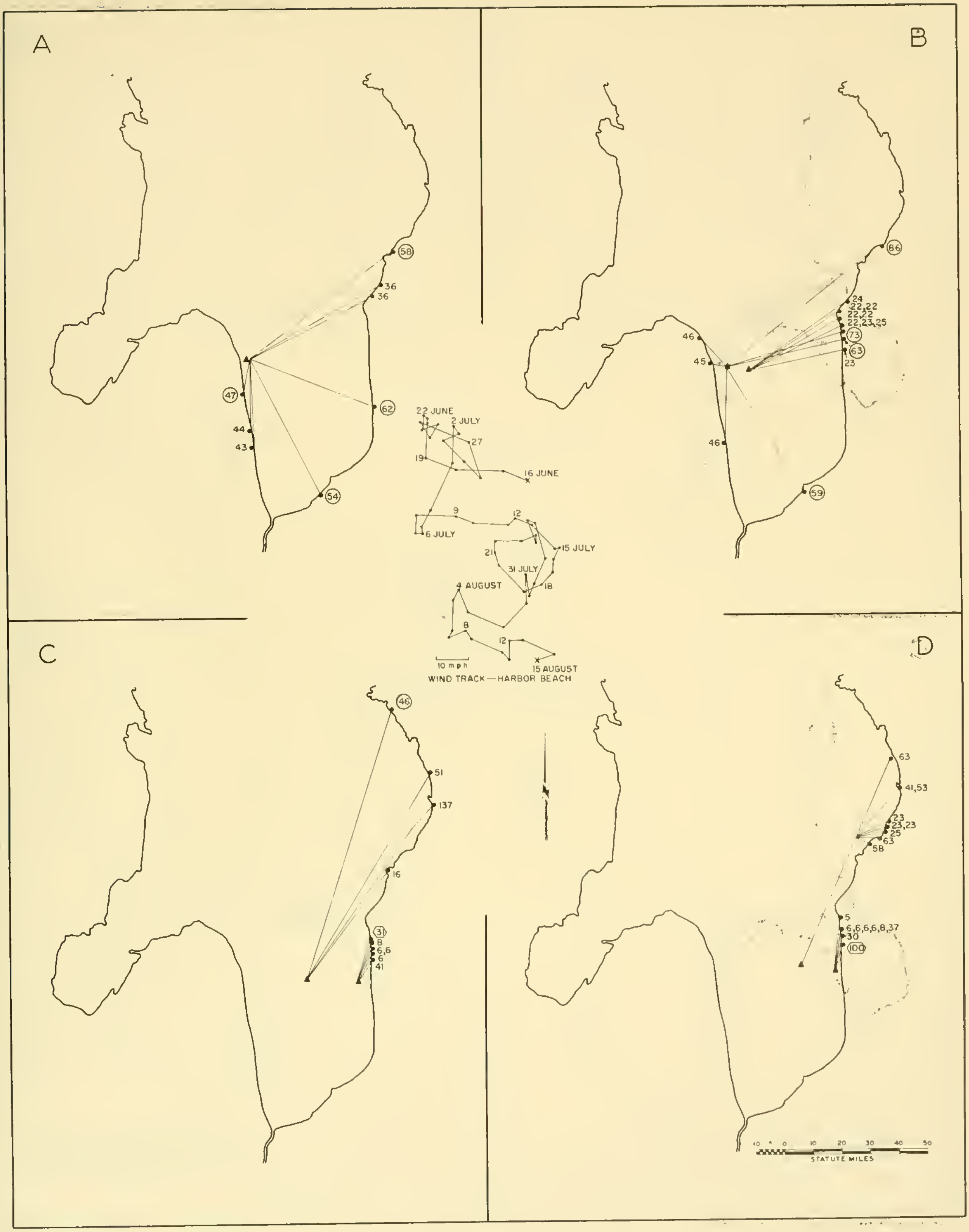

Figure 29.--Recovery points of drift bottles released June 22, 1956.

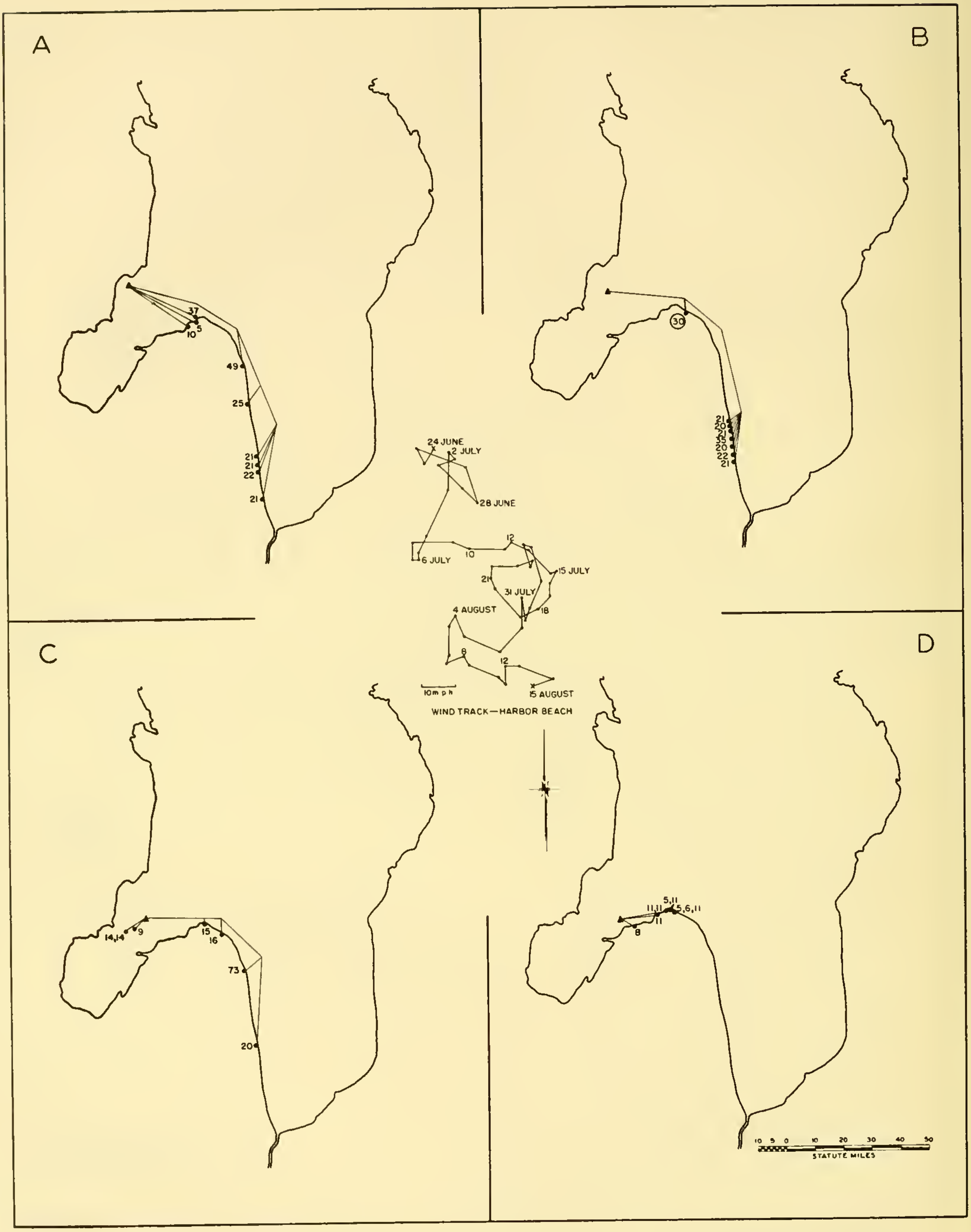

Figure 30.--Recovery points of drift bottles released June 29, 1956.

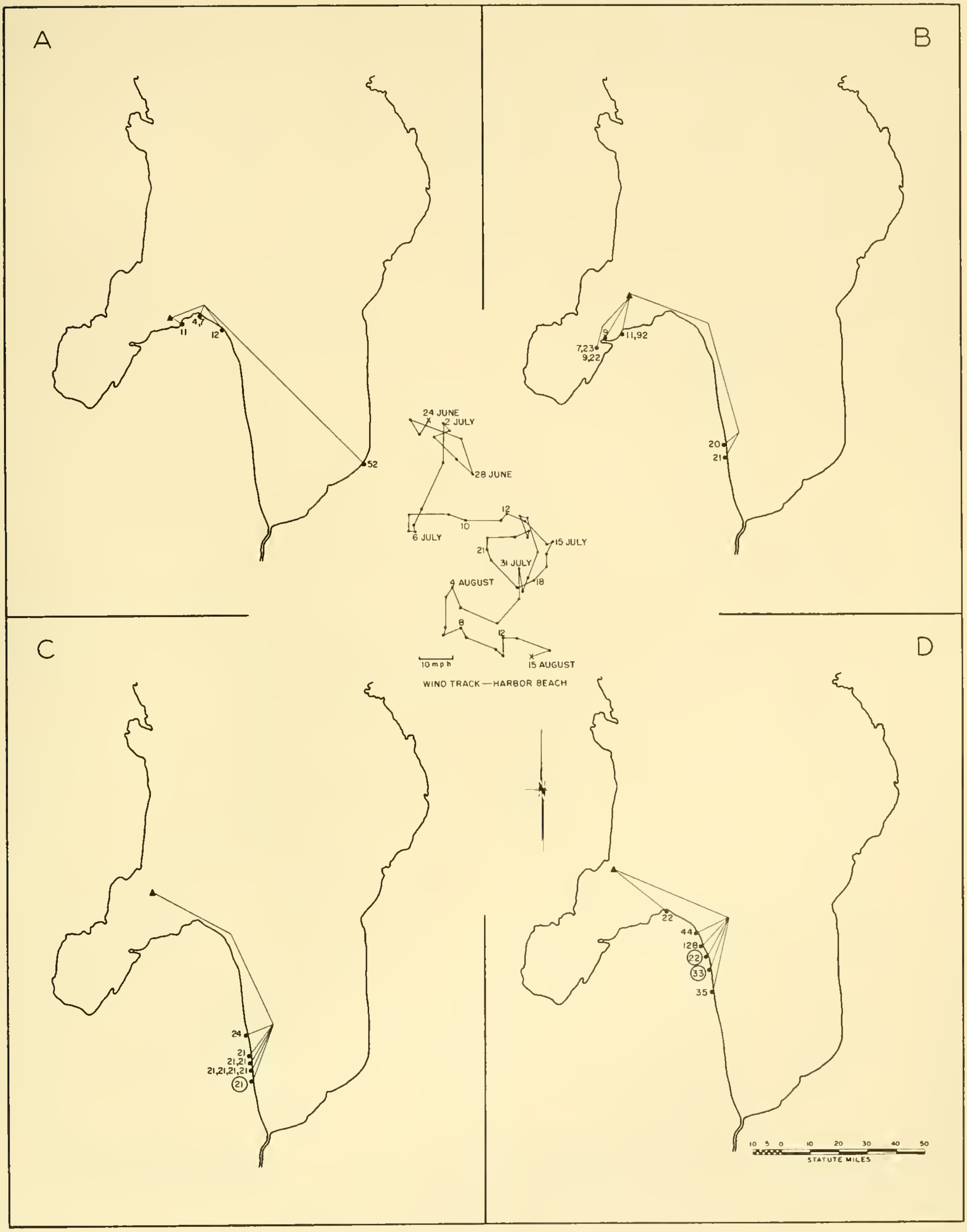

Figure 31.--Recovery points of drift bottles released June 29, 1956.

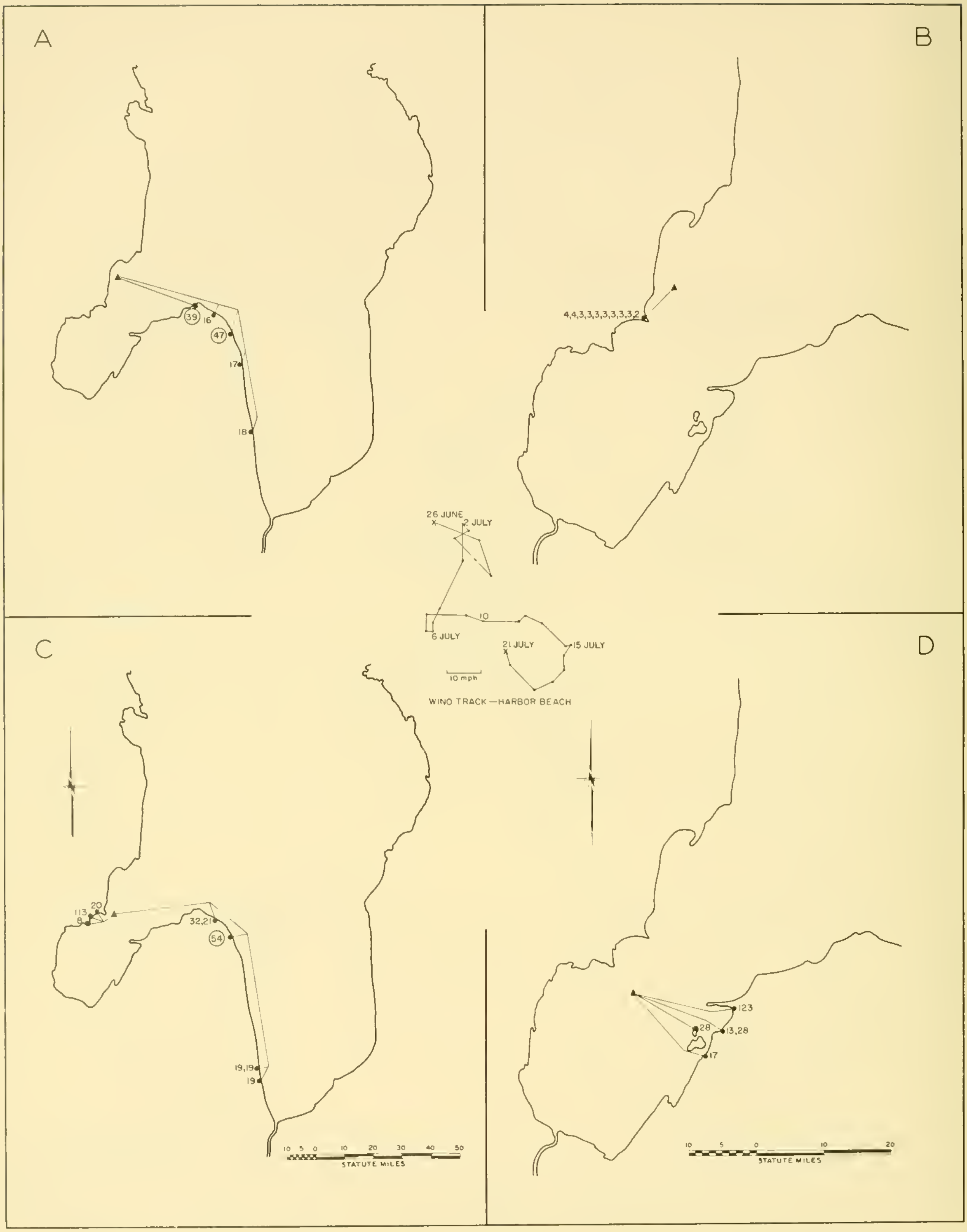

Figure 32.--Recovery points of drift bottles released July 1, 1956.

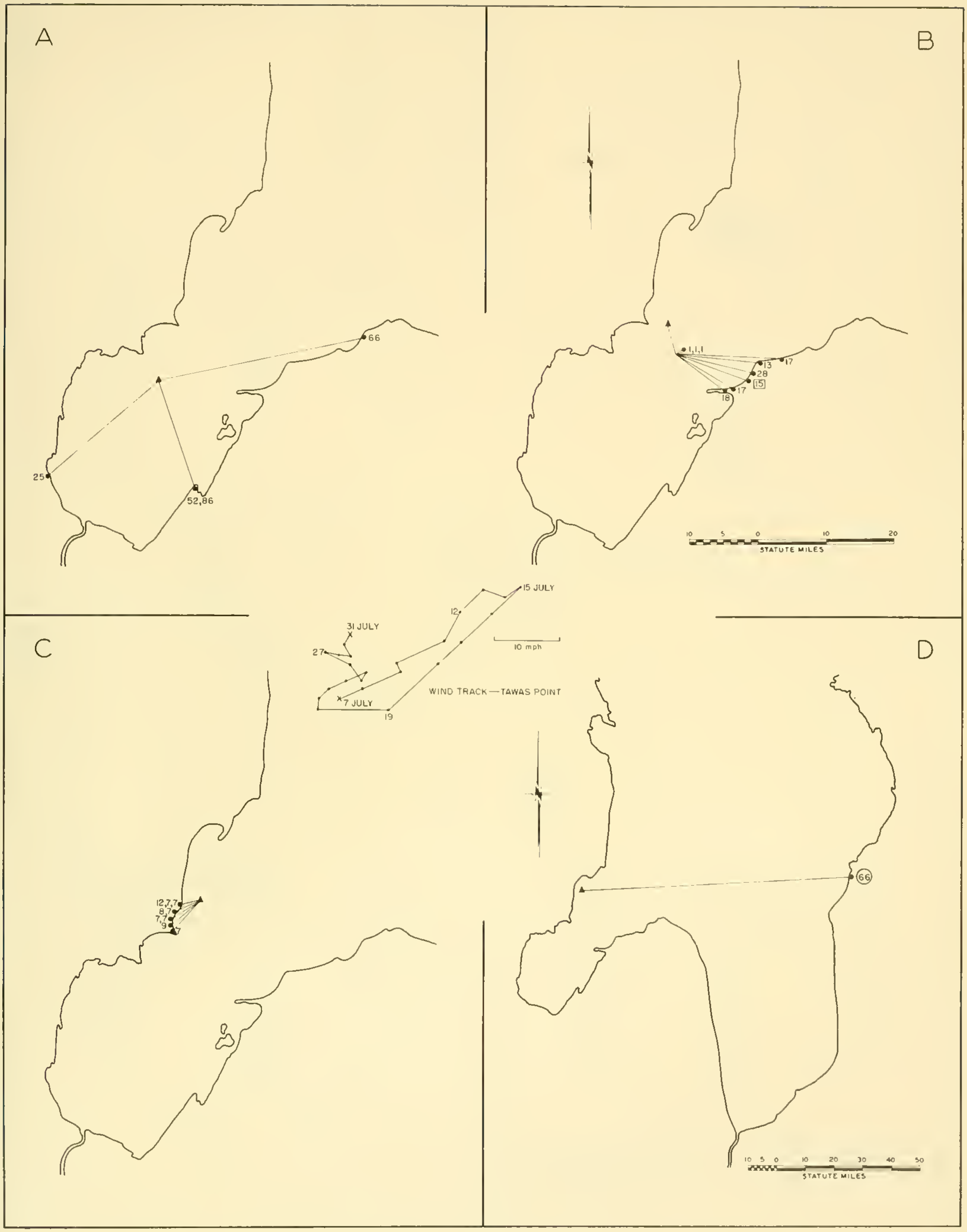

Figure 33.--Recovery points of drift bottles released July 12, 1956.

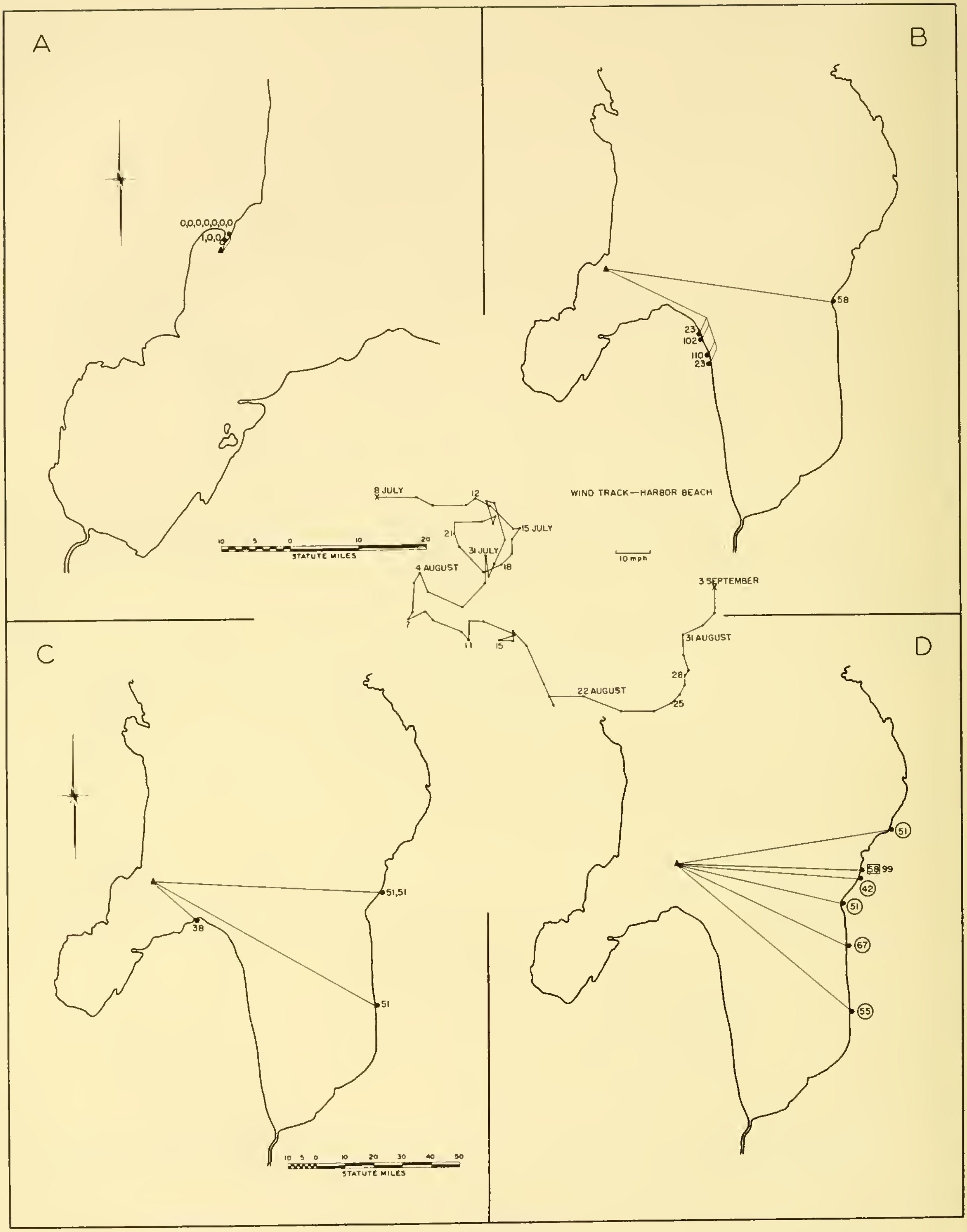

Figure 34.--Recovery points of drift bottles released July 13, 1956.

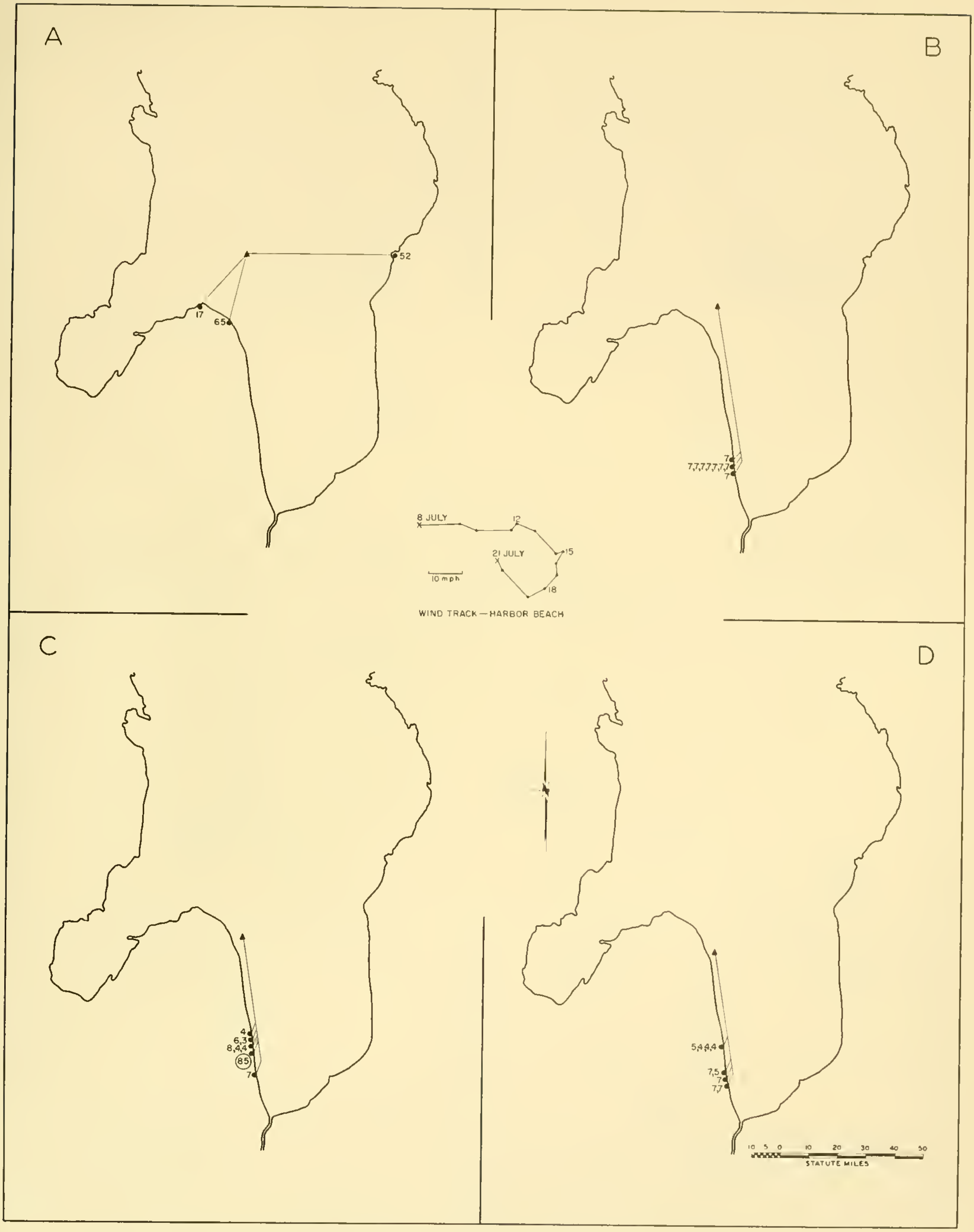

Figure 35.--Recovery points of drift bottles released July 13, 1956.

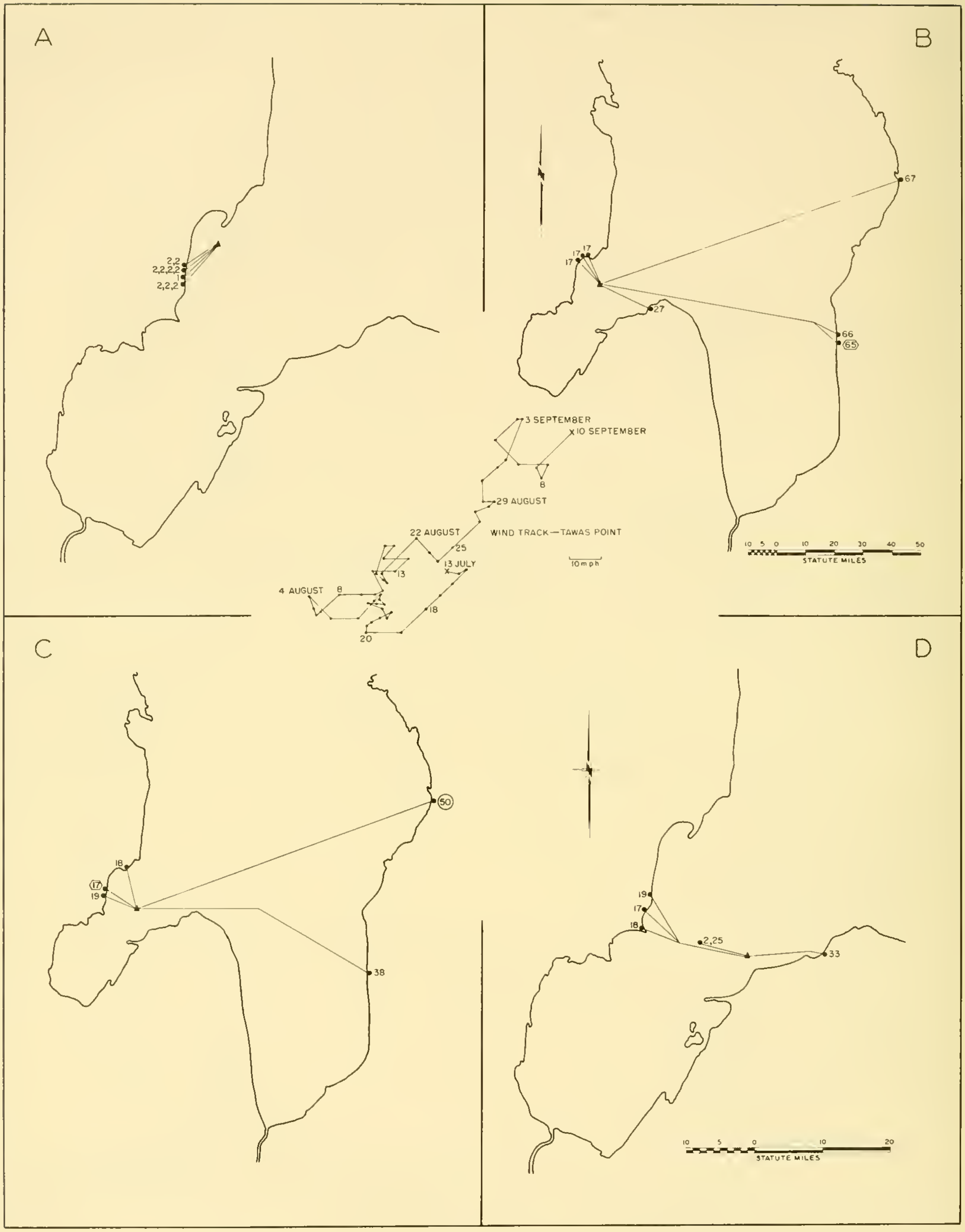

Figure 36.--Recovery points of drift bottles released July 18, 1956.

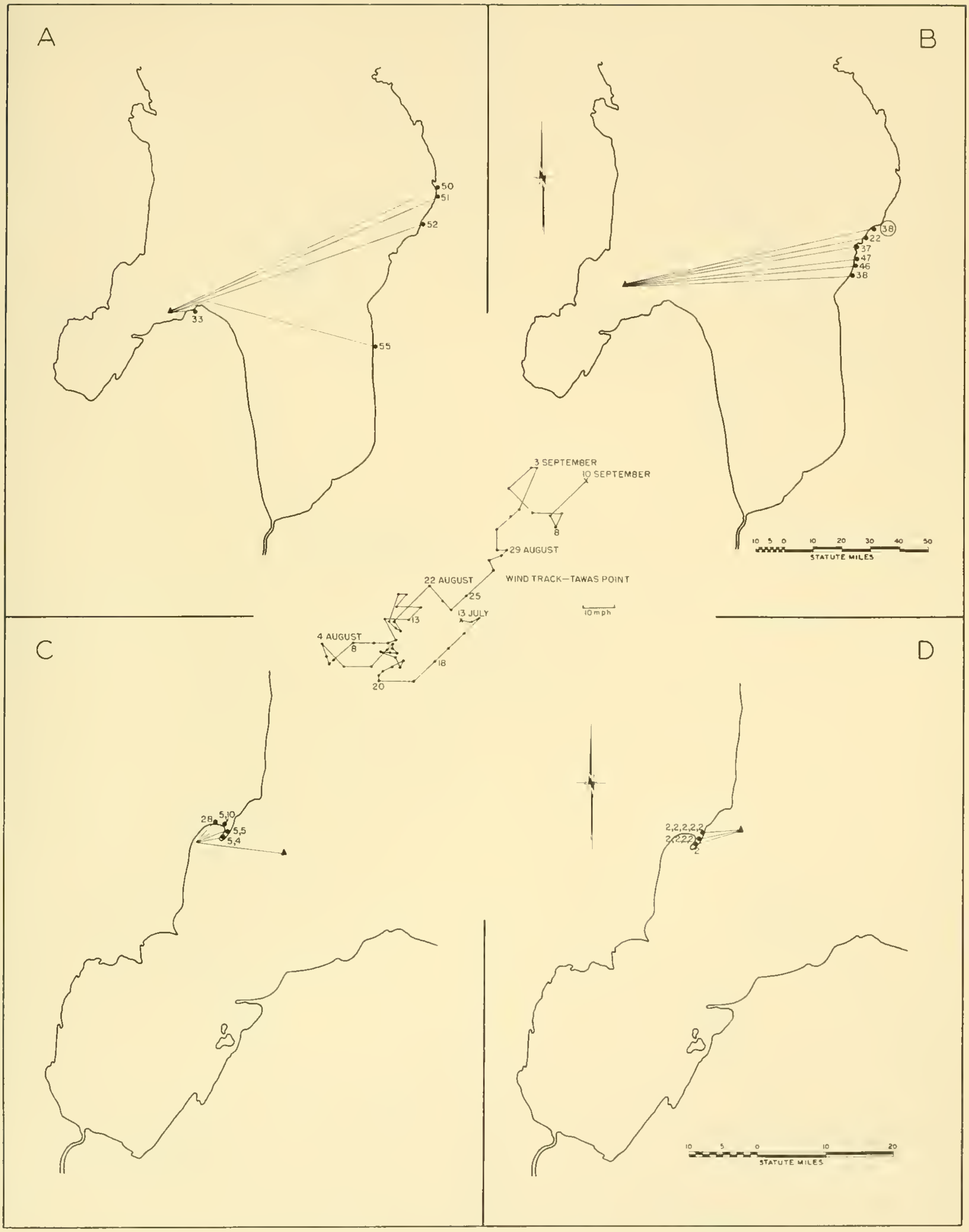

Figure 37.--Recovery points of drift bottles released July 18, 1956.

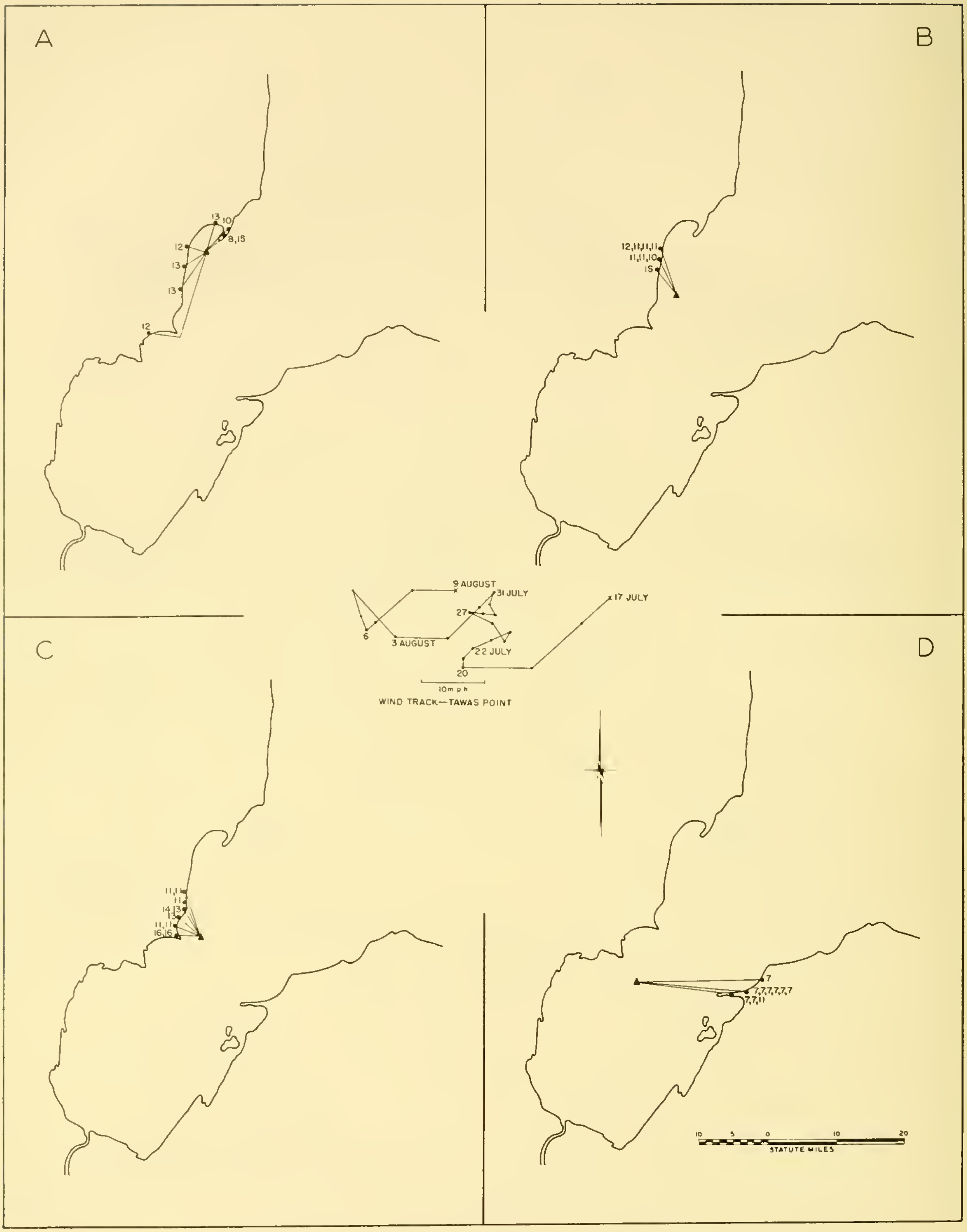

Figure 38.--Recovery points of drift bottles released July 22, 1956.

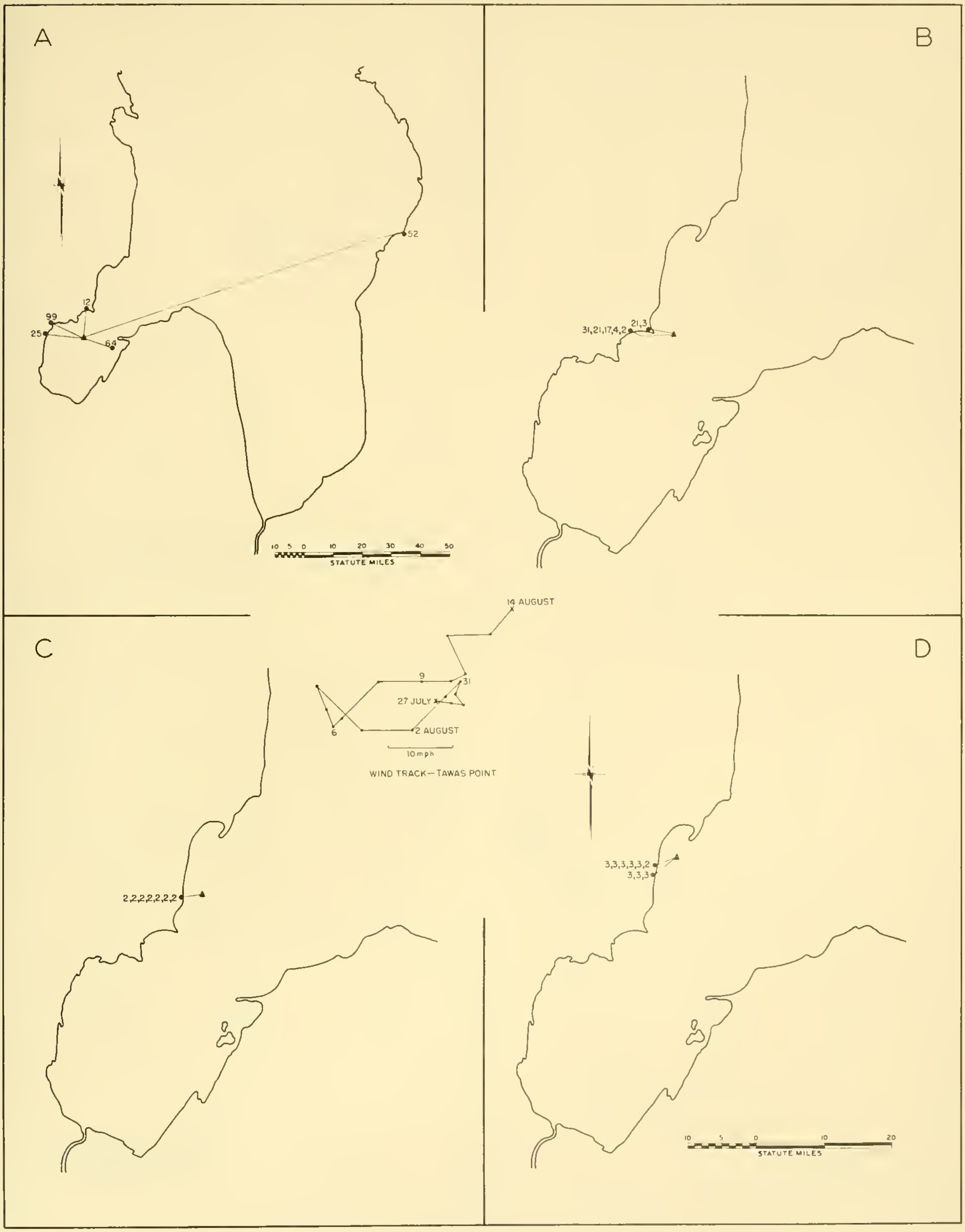

Figure 39.--Recovery points of drift bottles released August 1, 1956.

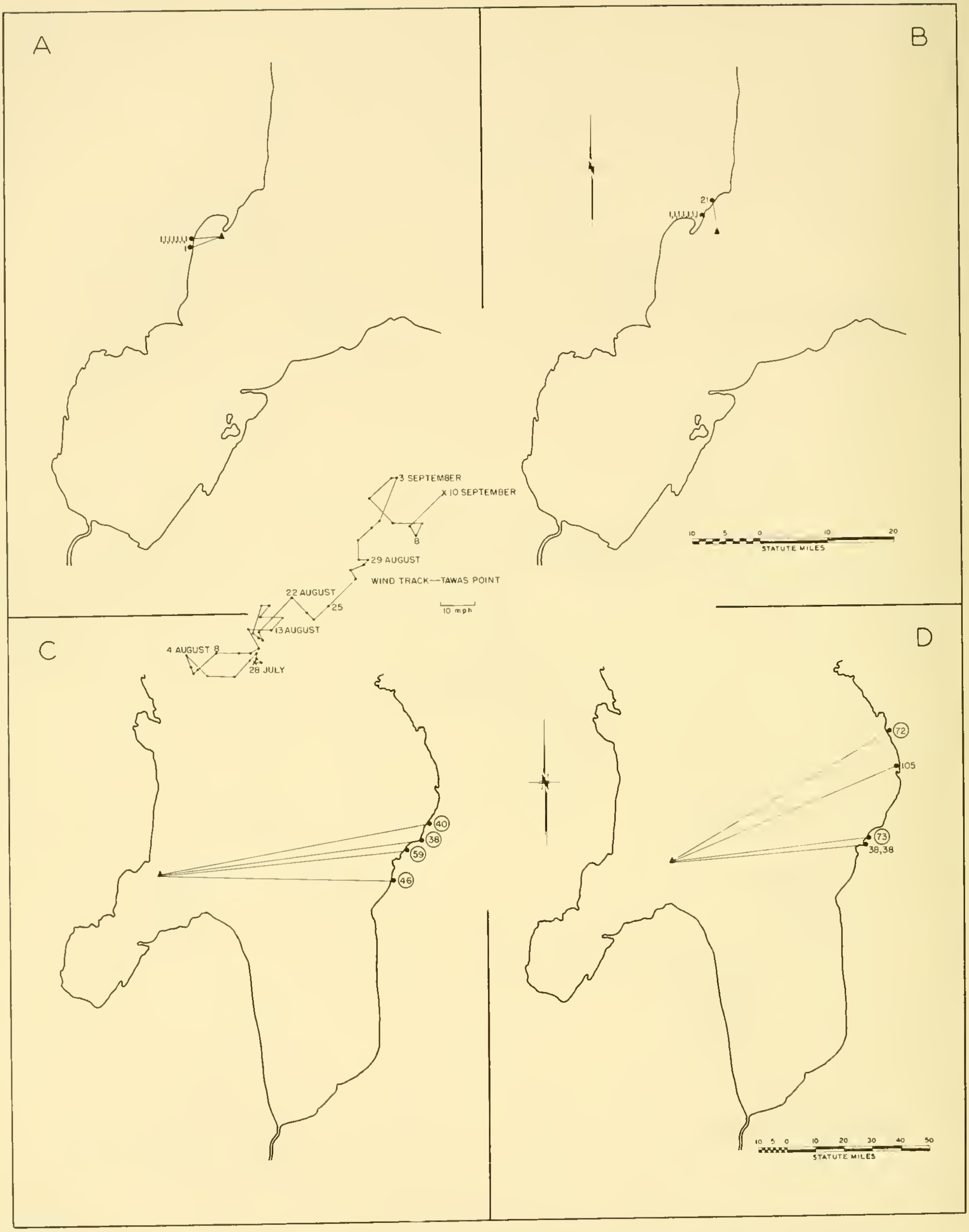

Figure 40.--Recovery points of drift bottles released August 2, 1956.

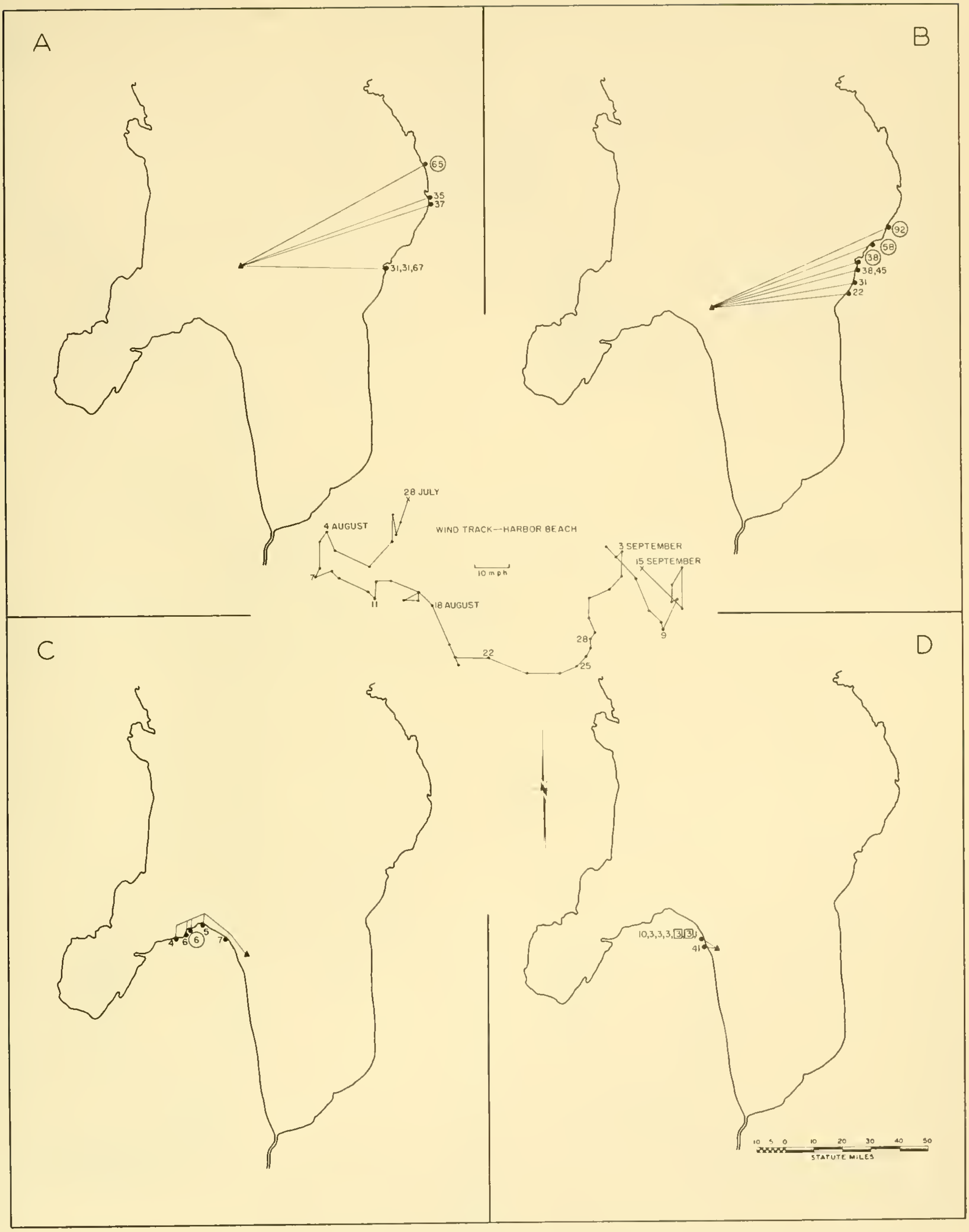

Figure 41.--Recovery points of drift bottles released August 2, 1956.

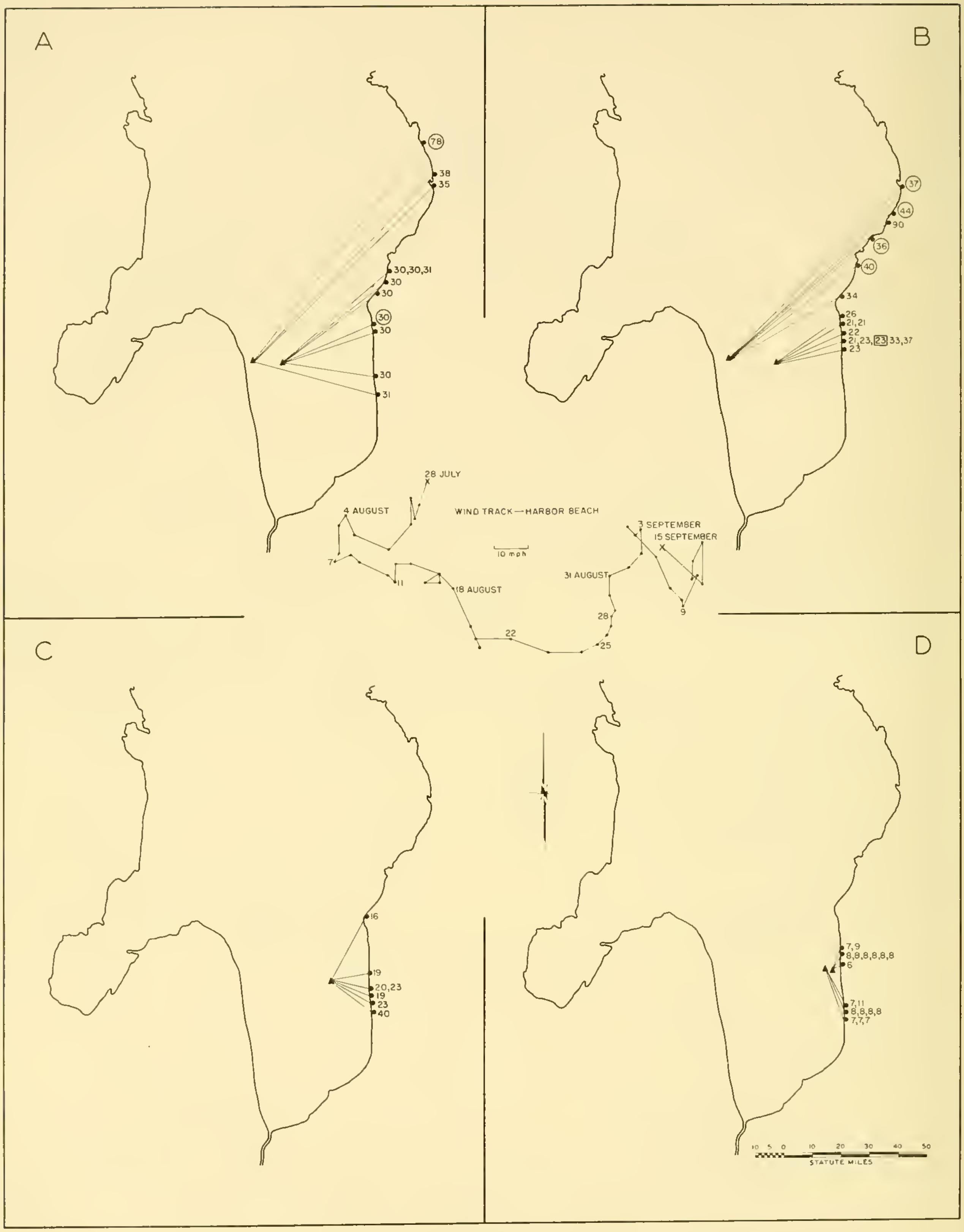

Figure 42.--Recovery points of drift bottles released August 3, 1956.

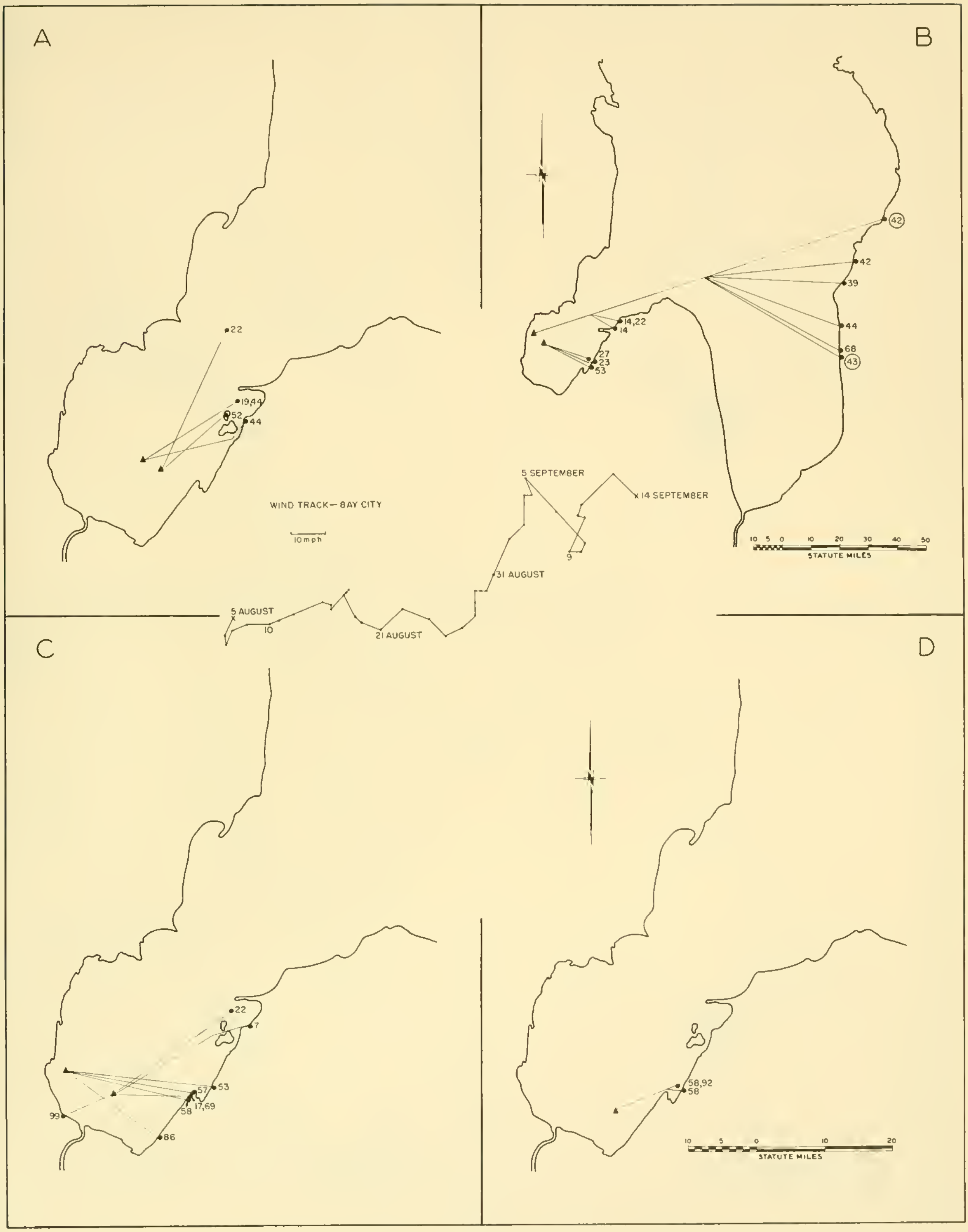

Figure 43.--Recovery points of drift bottles released August 10, 1956.

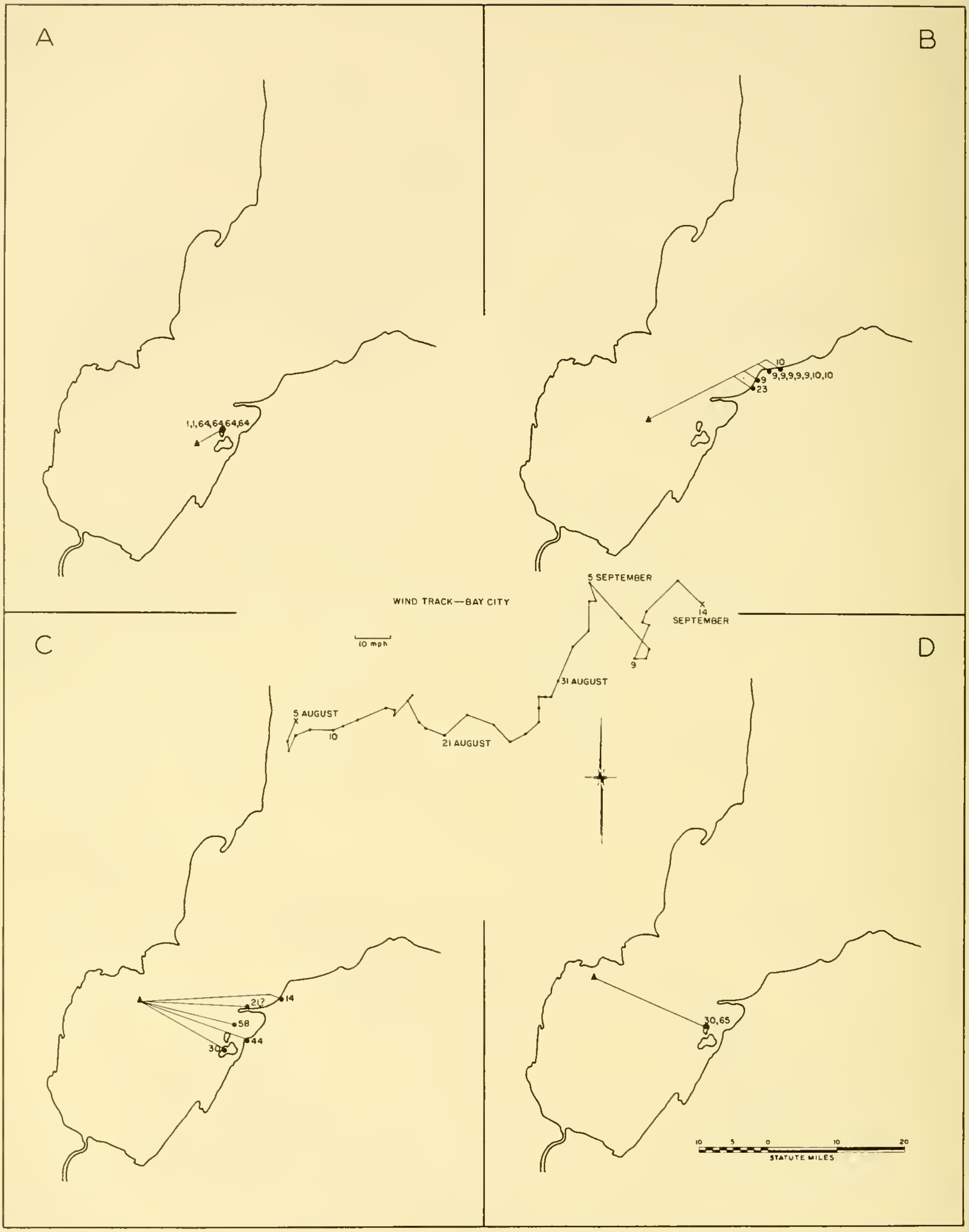

Figure 44.--Recovery points of drift bottles released August 10, 1956.

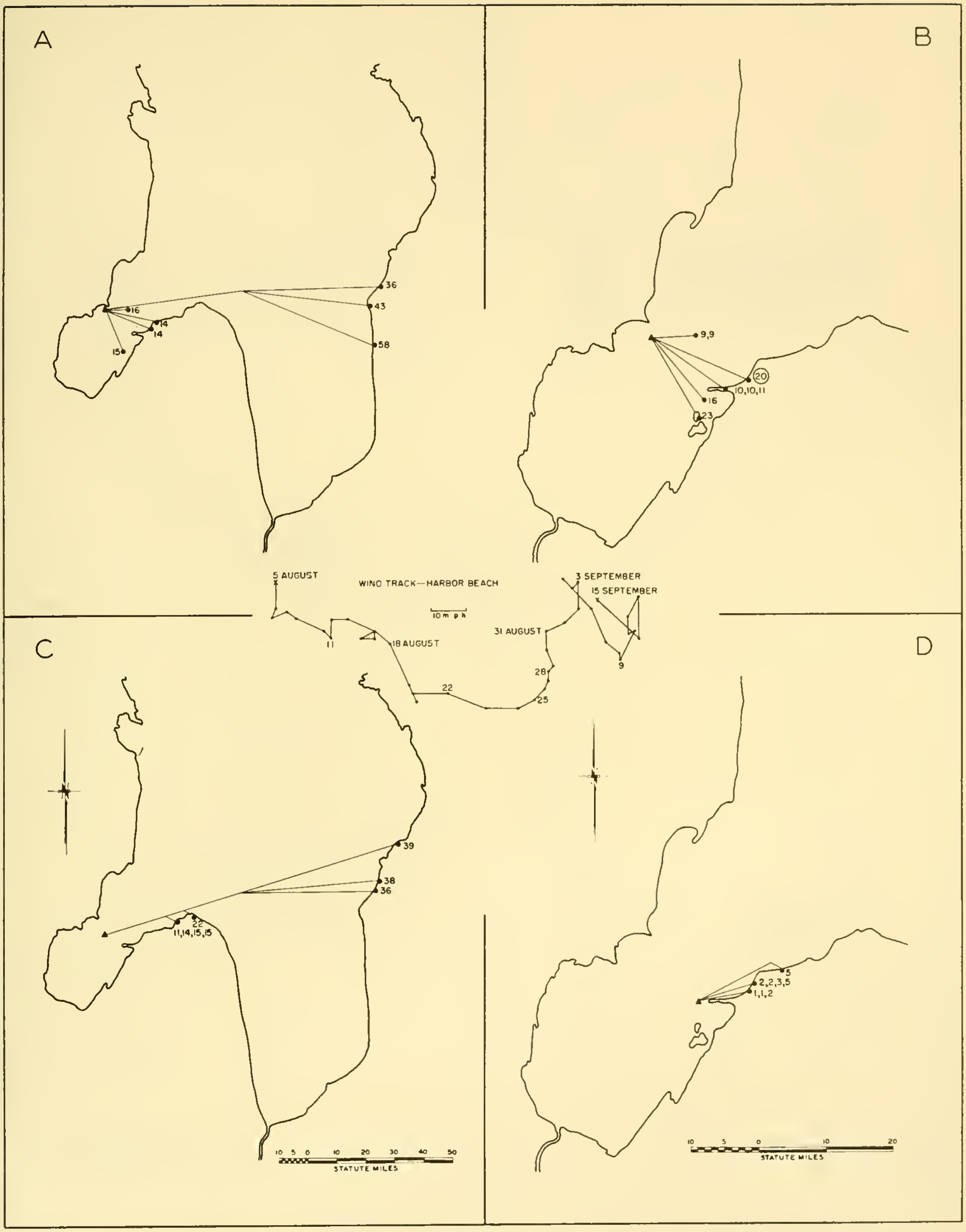

Figure 45.--Recovery points of drift bottles released August 10, 1956.

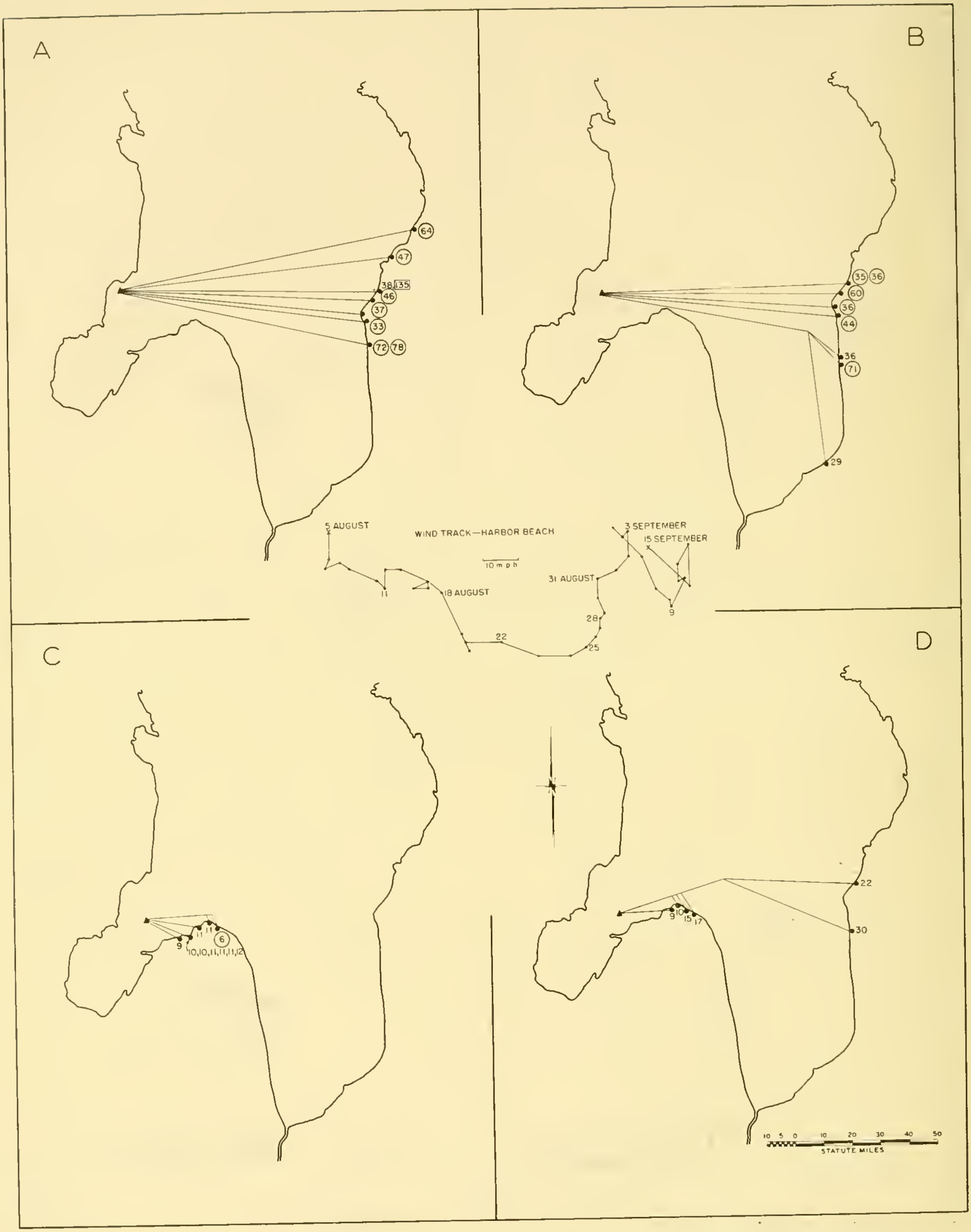

Figure 46.--Recovery points of drift bottles released August 10, 1956.

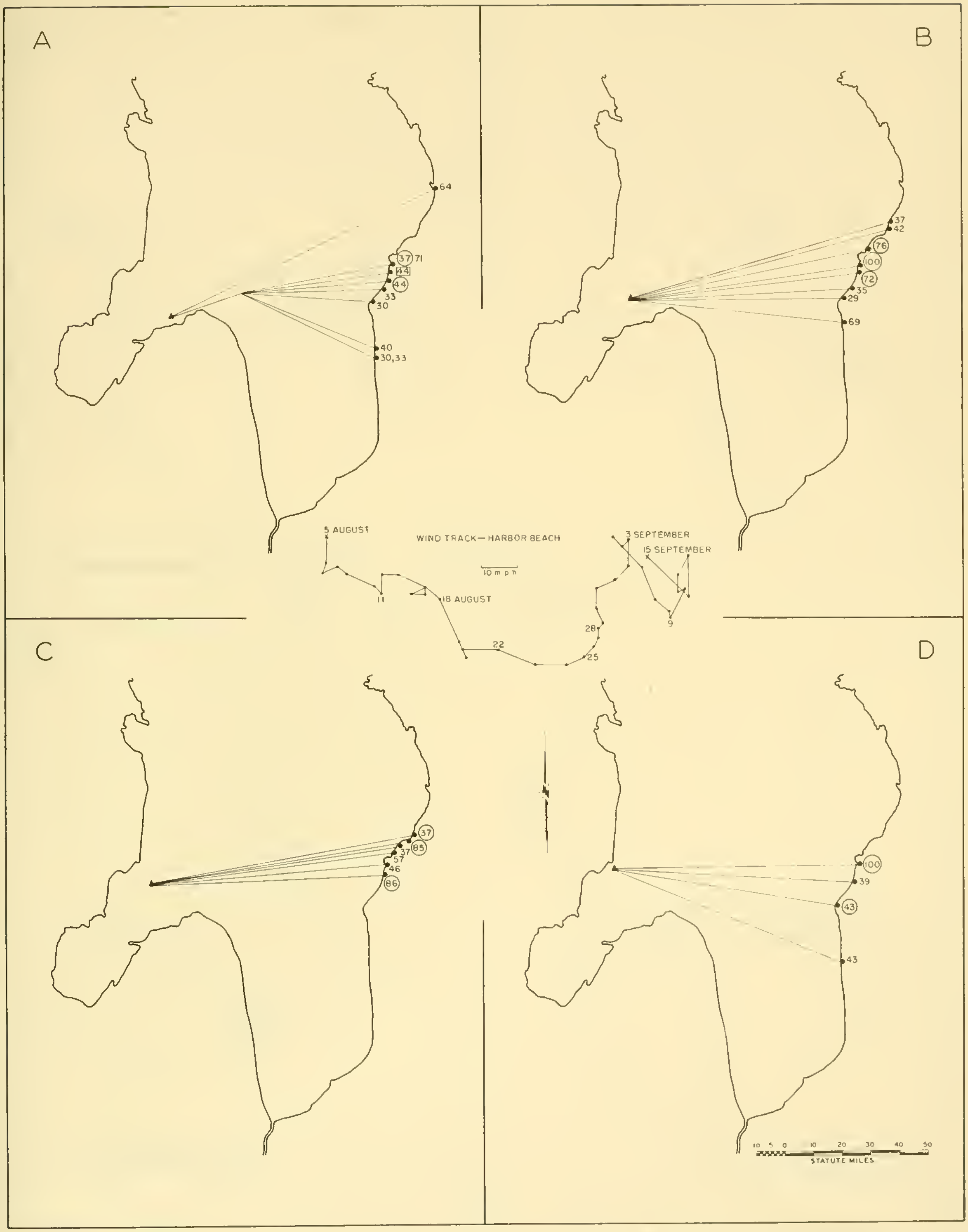

Figure 47.--Recovery points of drift bottles released August 10, 1956.

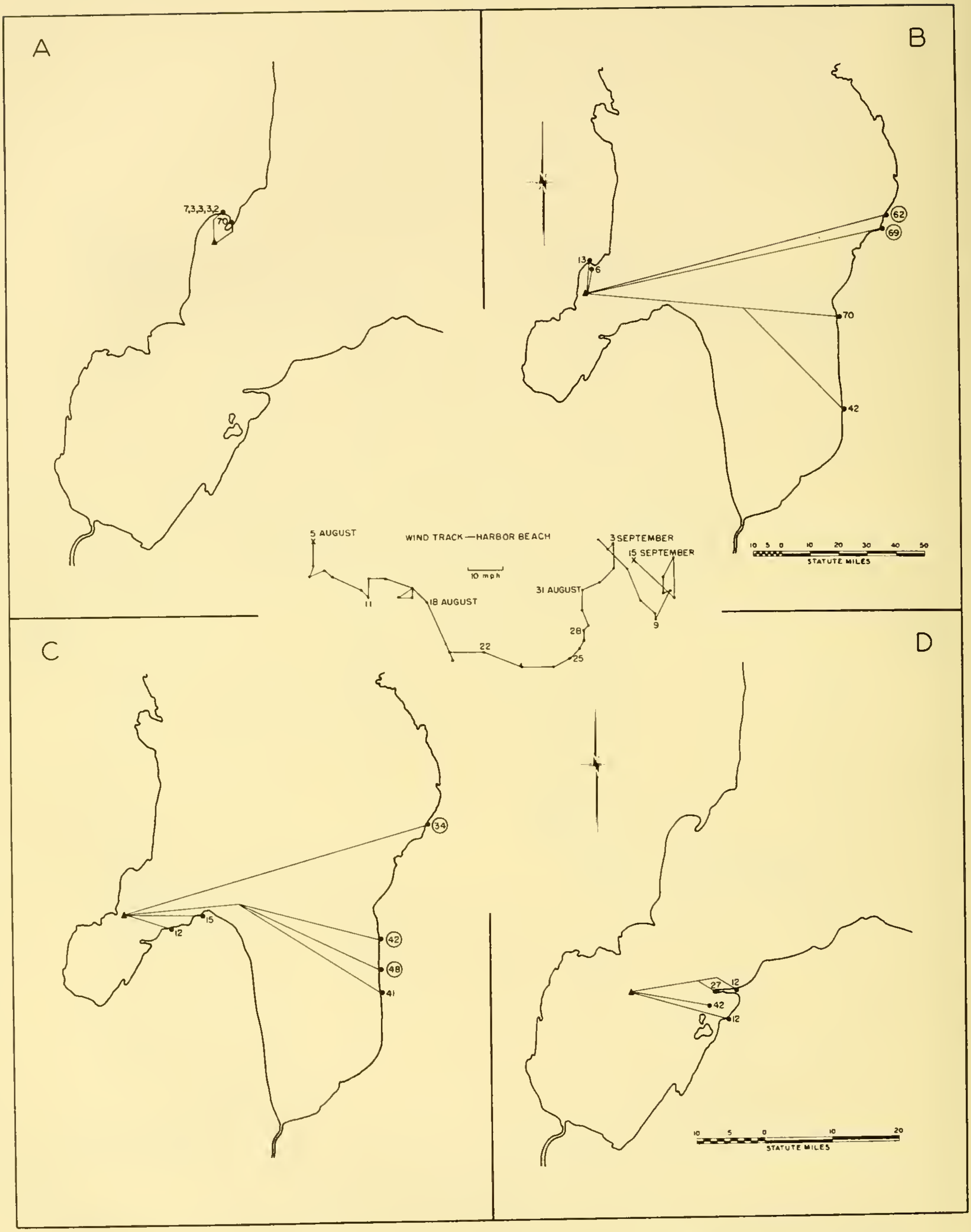

Figure 48.--Recovery points of drift bottles released August 12, 1956.

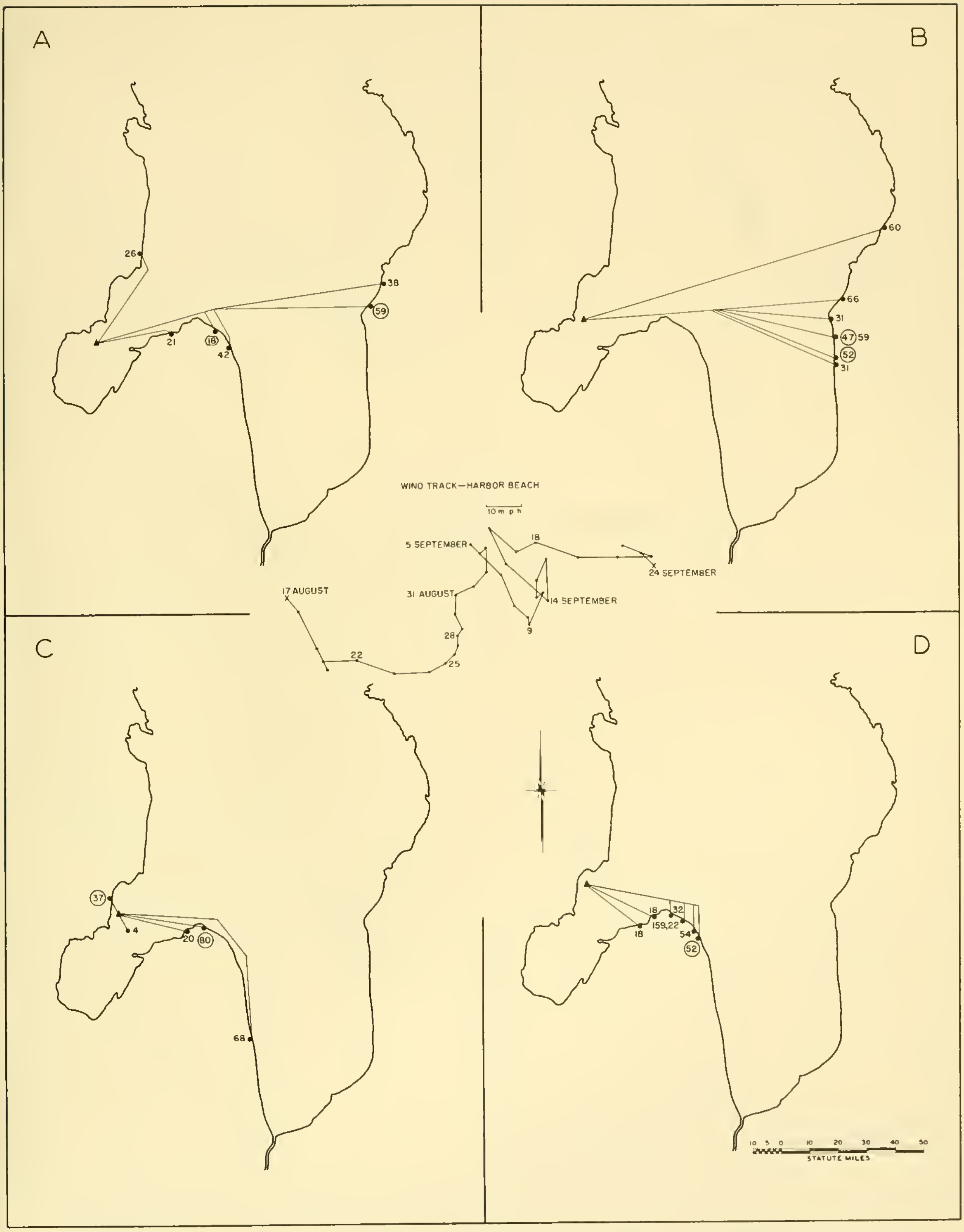

Figure 49.--Recovery points of drift bottles released August 22, 1956.

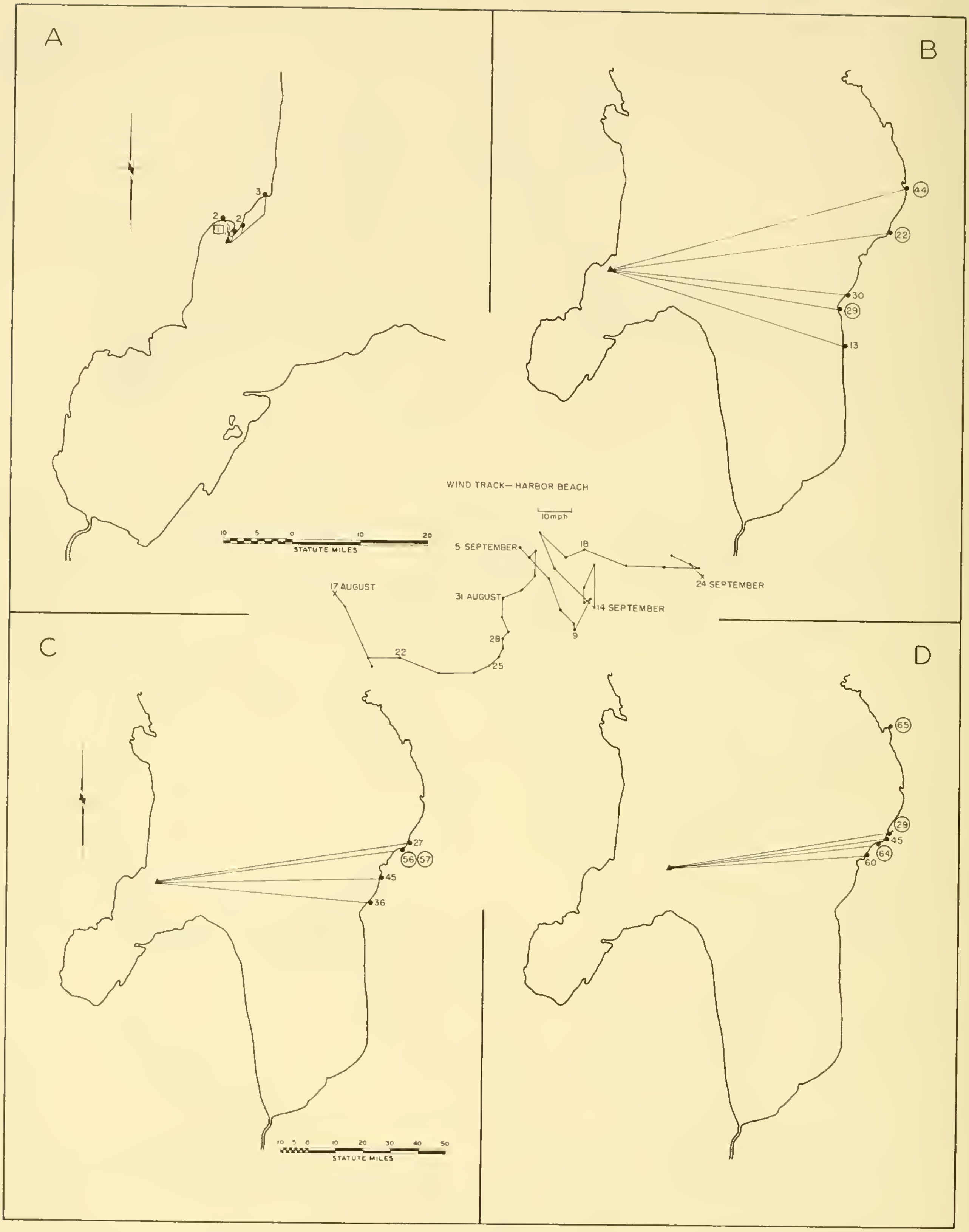

Figure 50.--Recovery points of drift bottles released August 24, 1956.

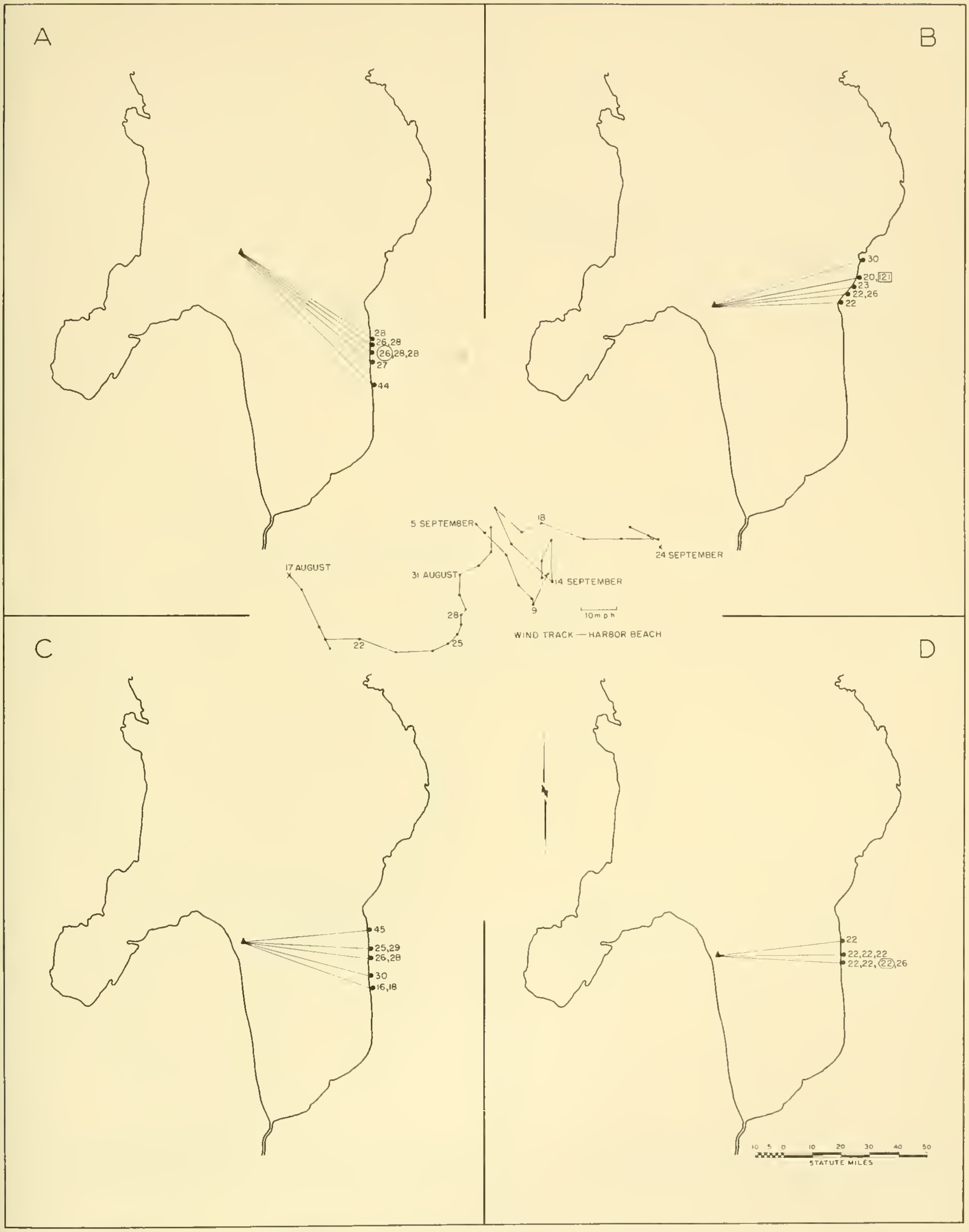

Figure 51.--Recovery points of drift bottles released August 24, 1956.

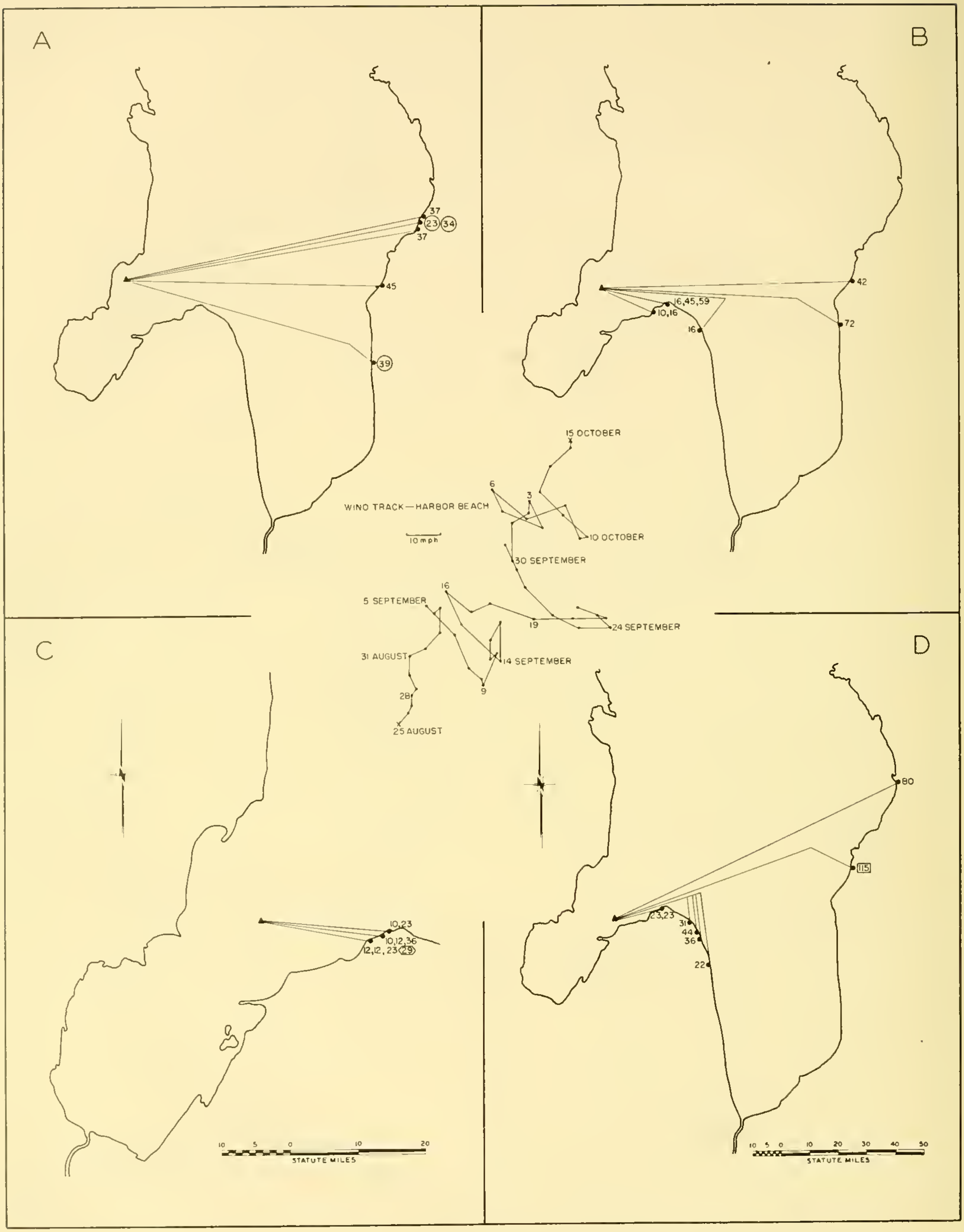

Figure 52.--Recovery points of drift bottles released August 30, 1956.

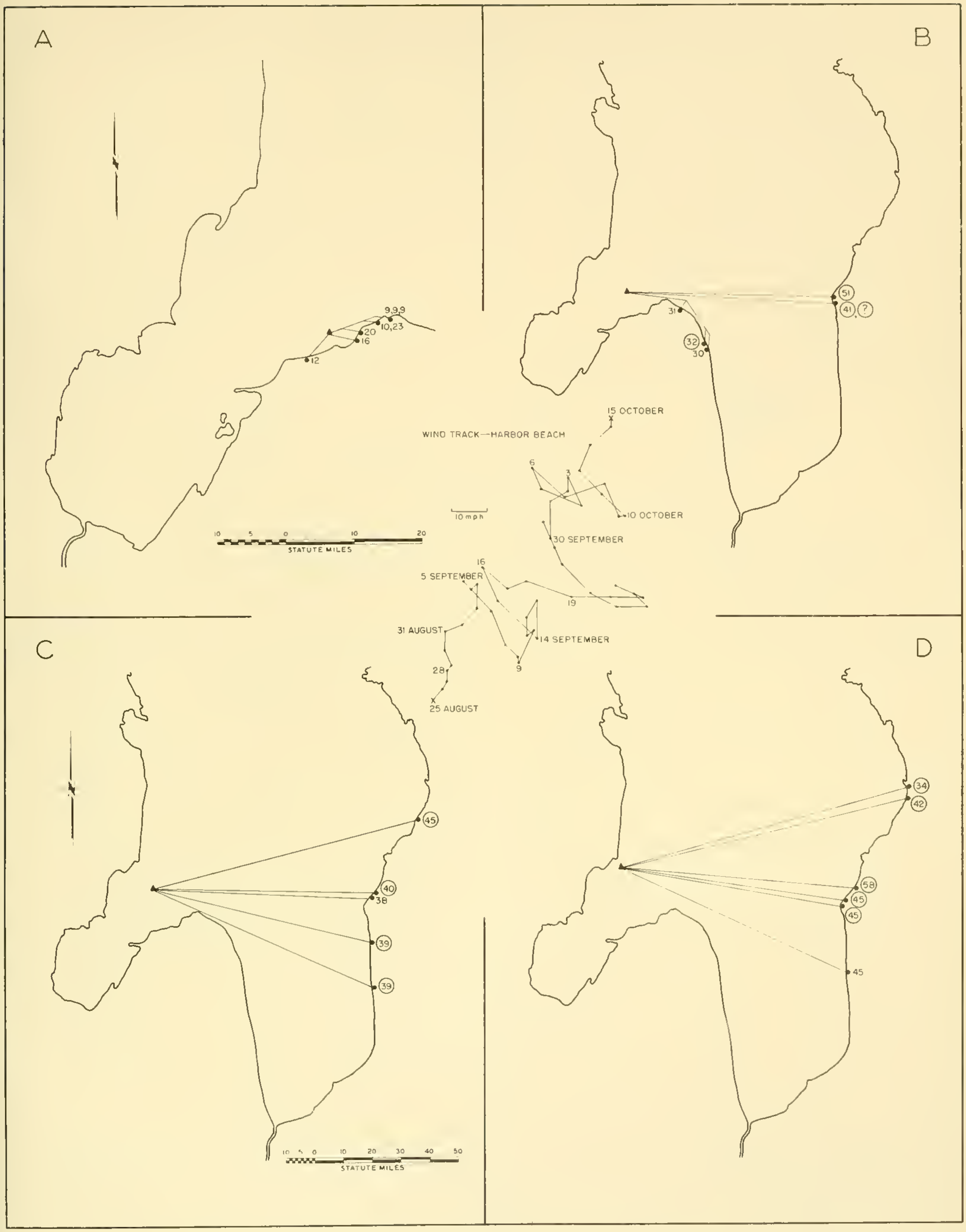

Figure 53.--Recovery points of drift bottles released August 30, 1956.

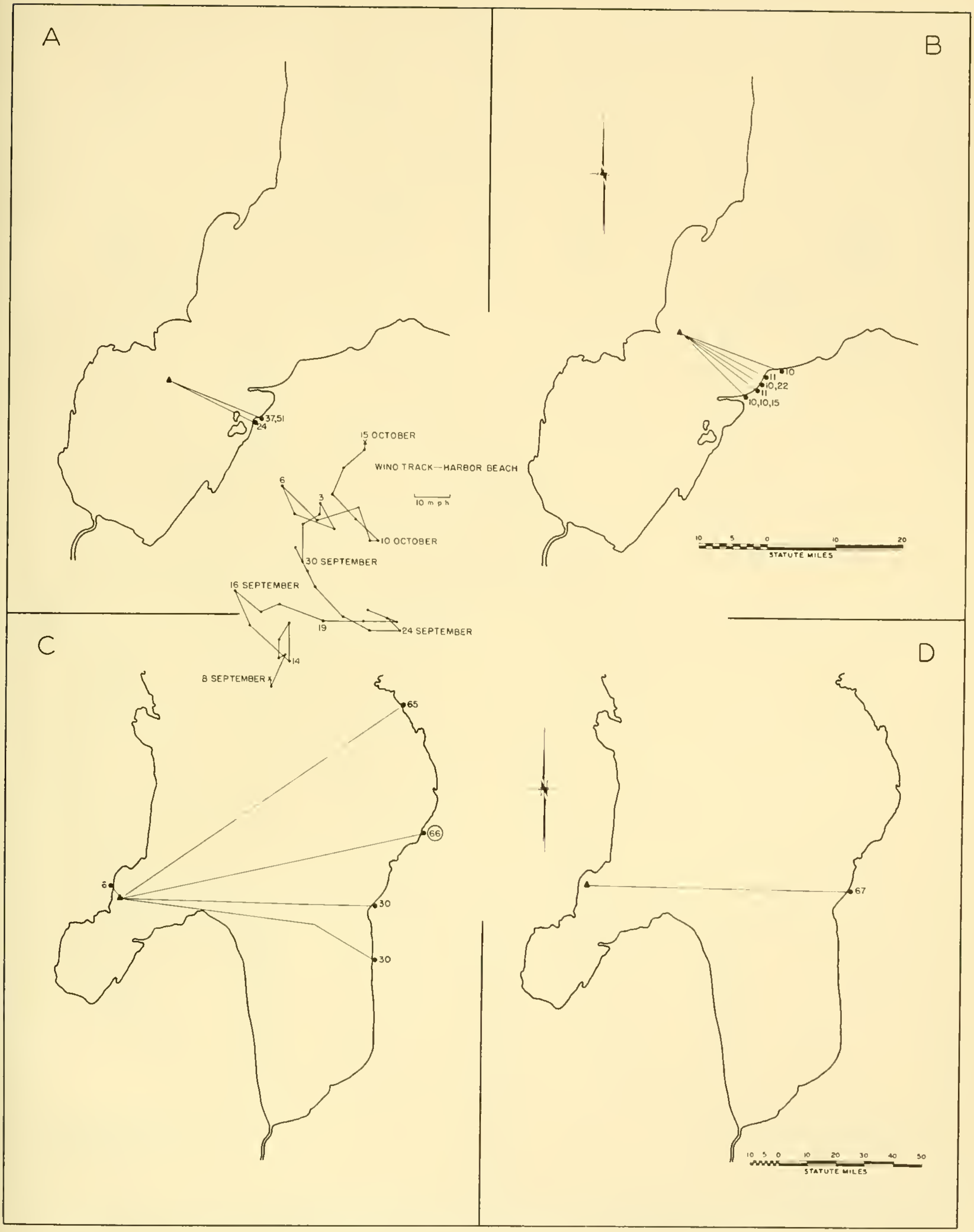

Figure 55.--Recovery points of drift bottles released September 12, 1956.

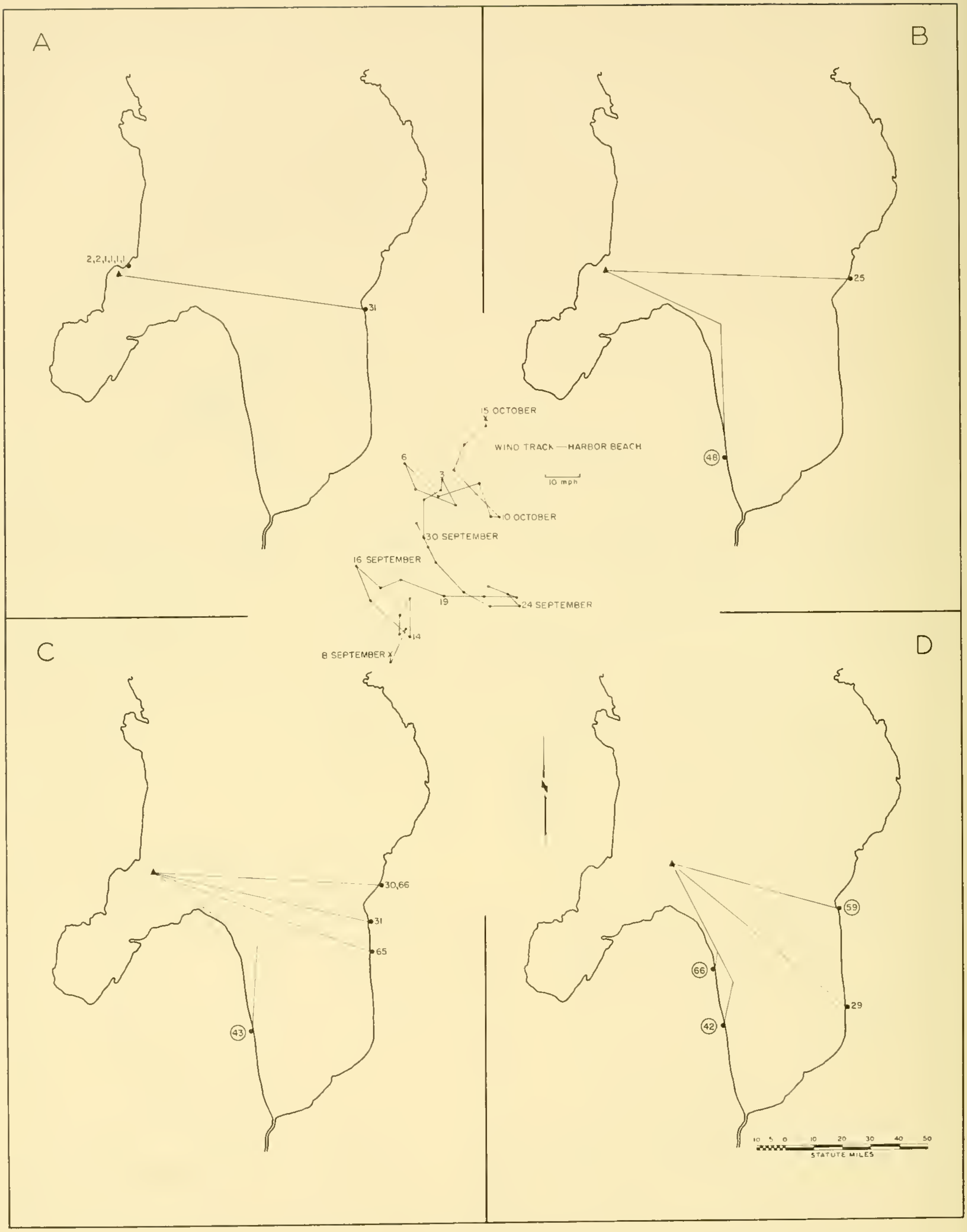

Figure 56.--Recovery points of drift bottles released September 13, 1956.

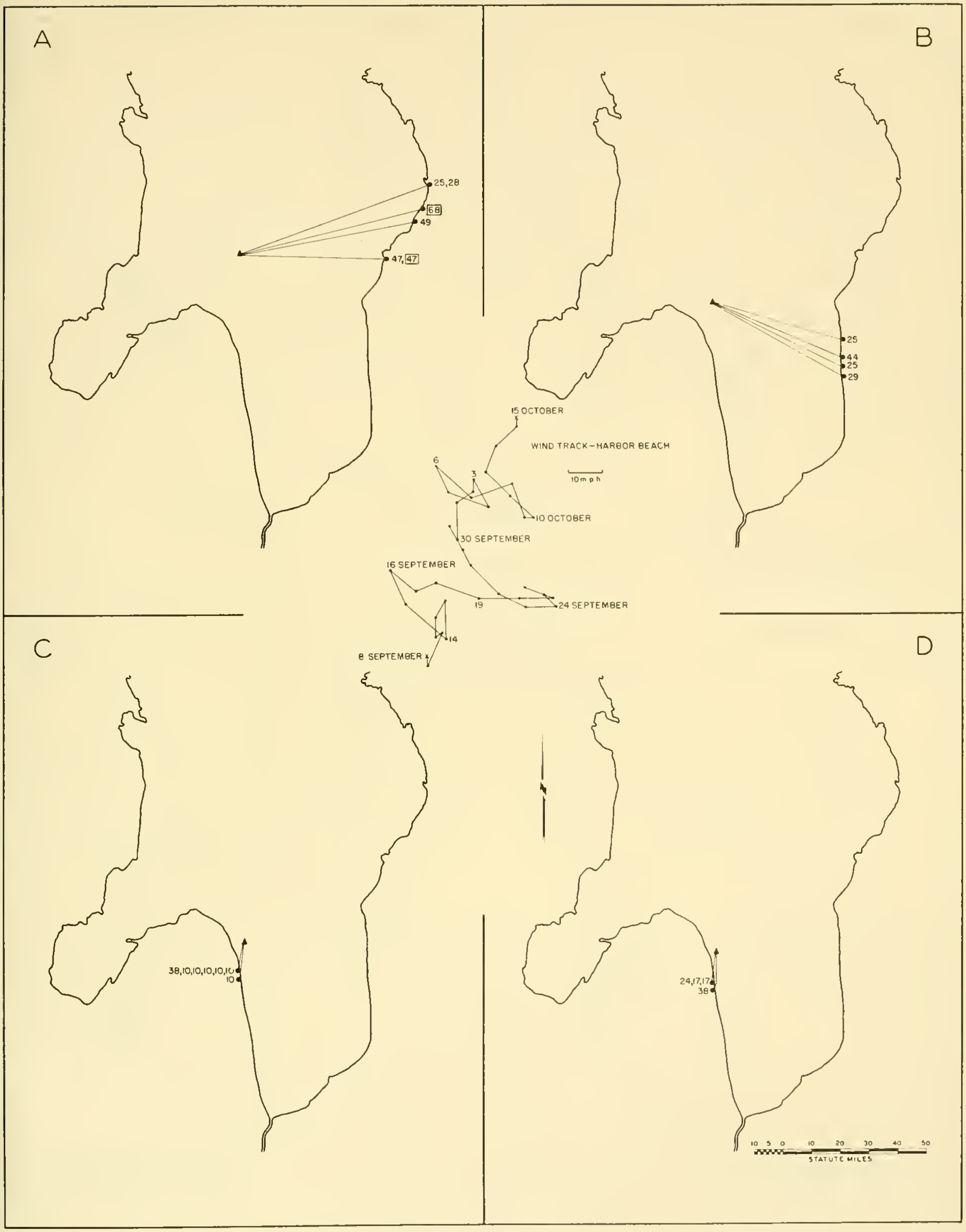

Figure 57.--Recovery points of drift bottles released September 13, 1956.

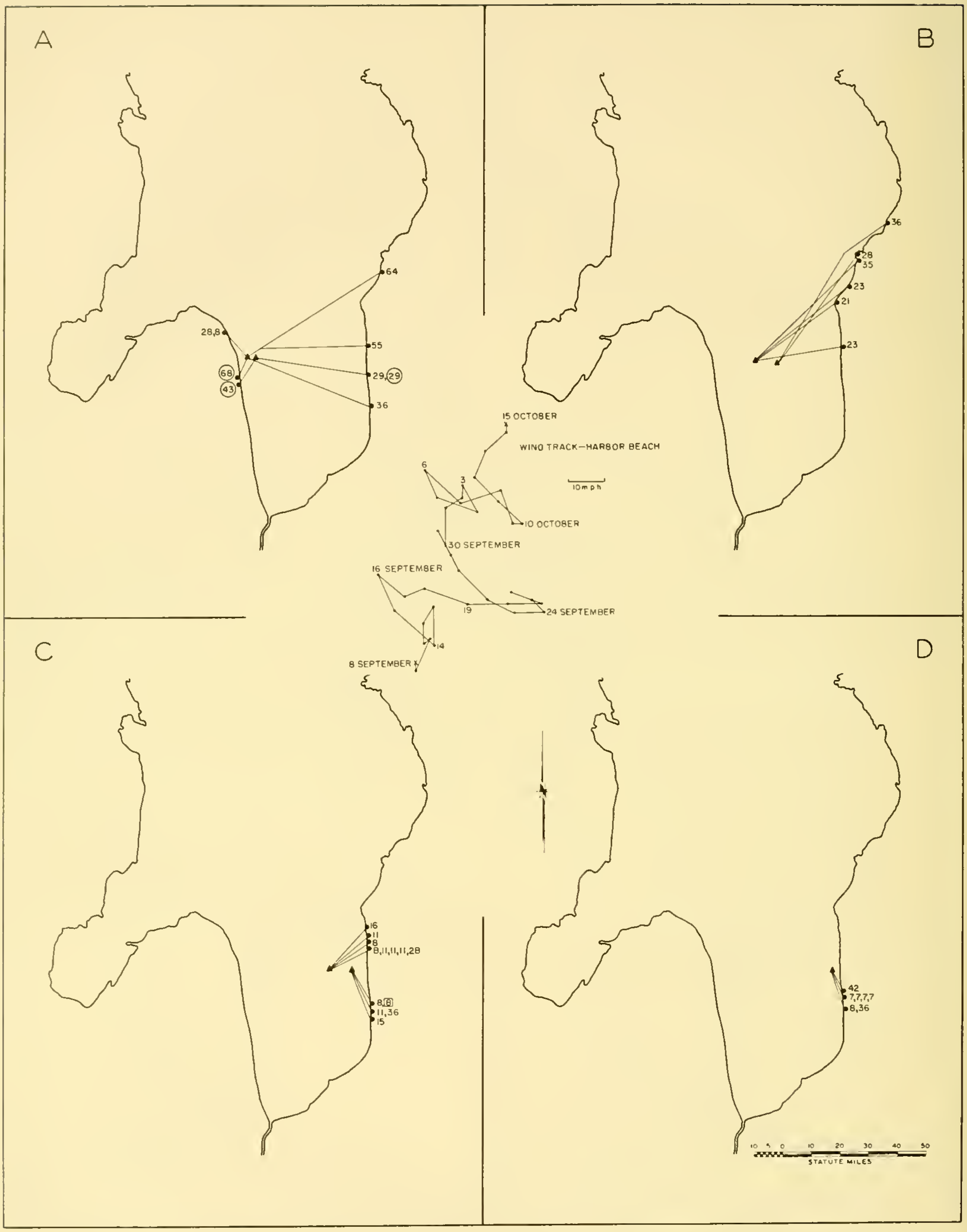

Figure 58.--Recovery points of drift bottles released September 15, 1956.

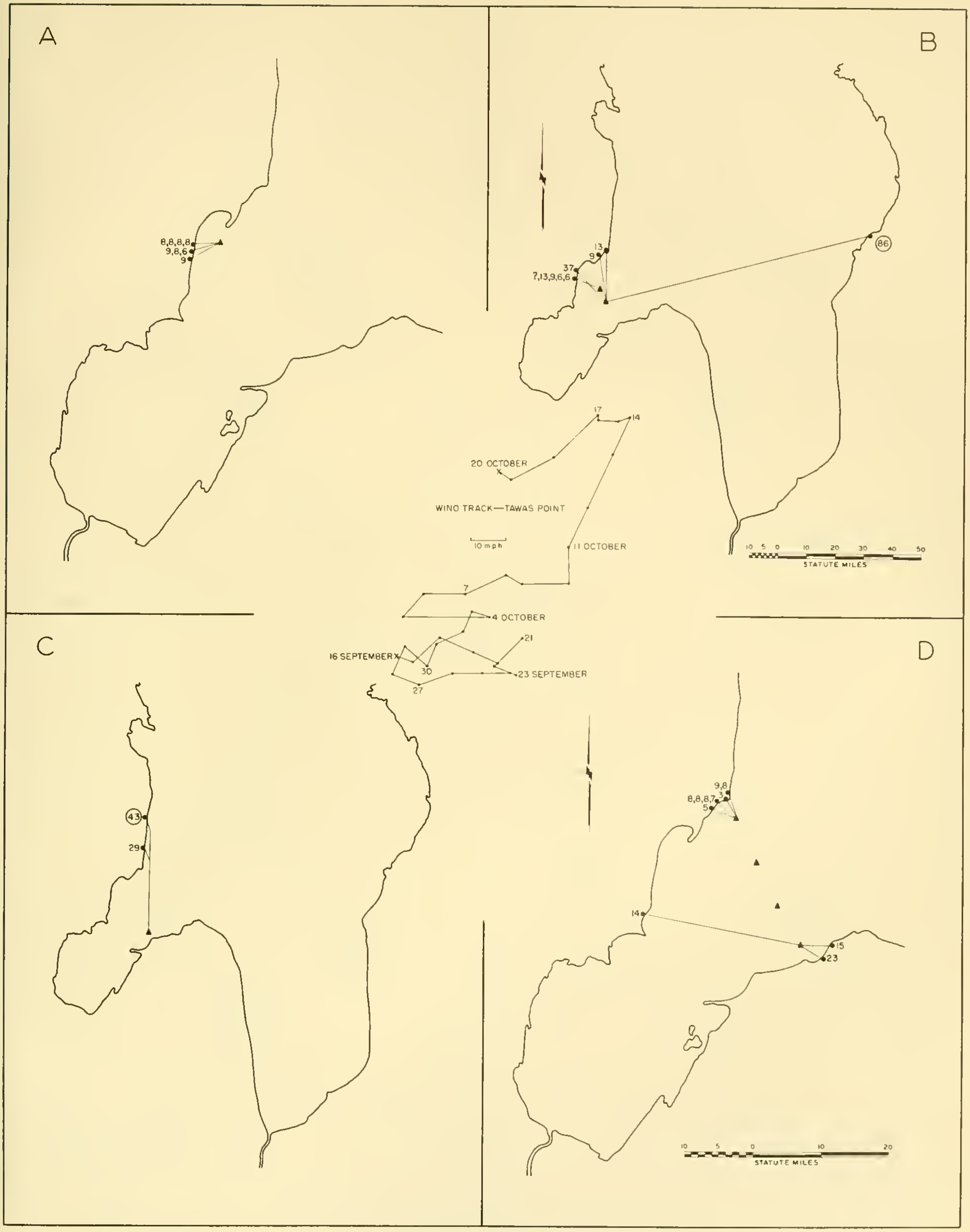

Figure 59.--Recovery points of drift bottles released September 21, 1956.

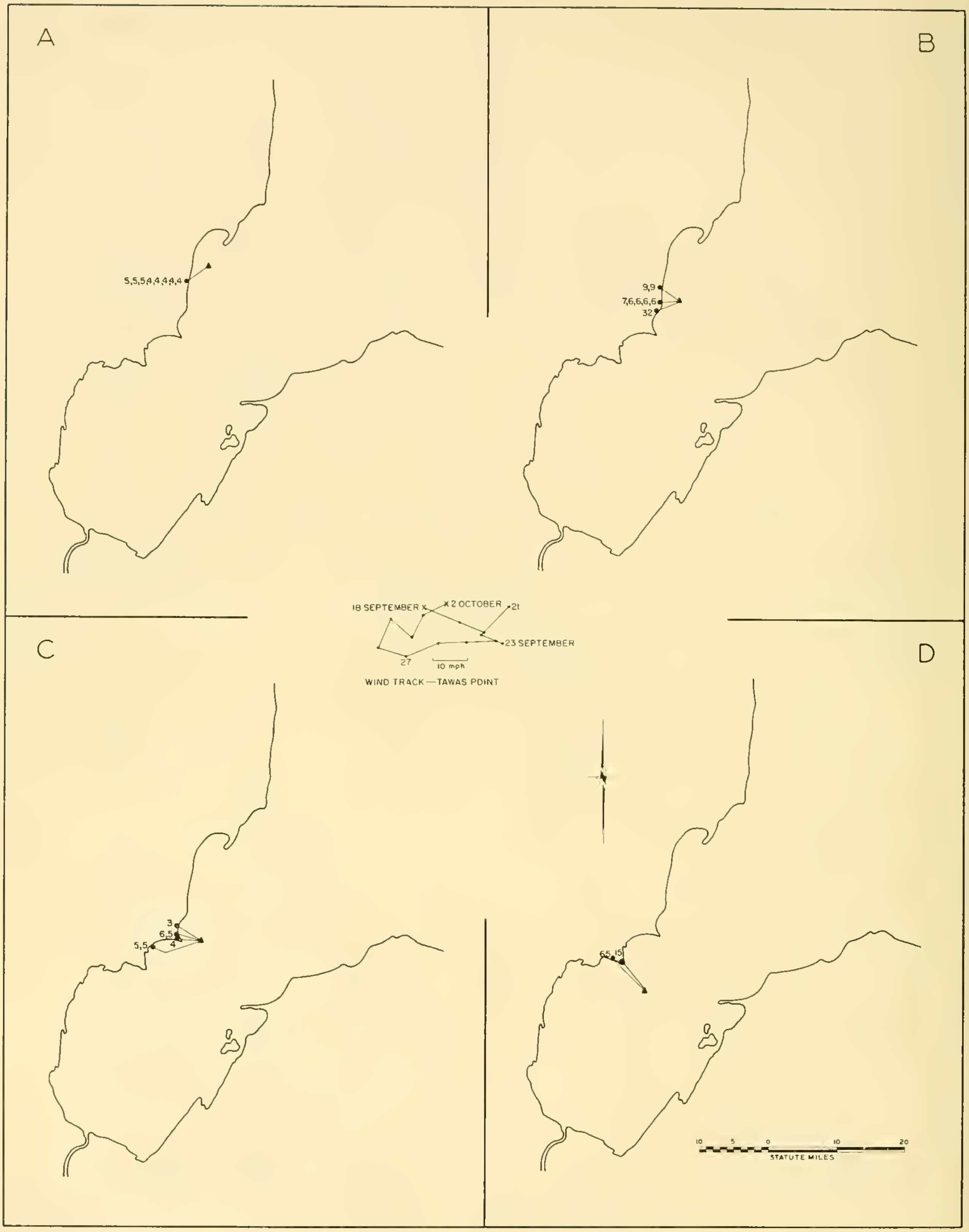

Figure 60.--Recovery points of drift bottles released September 23, 1956.

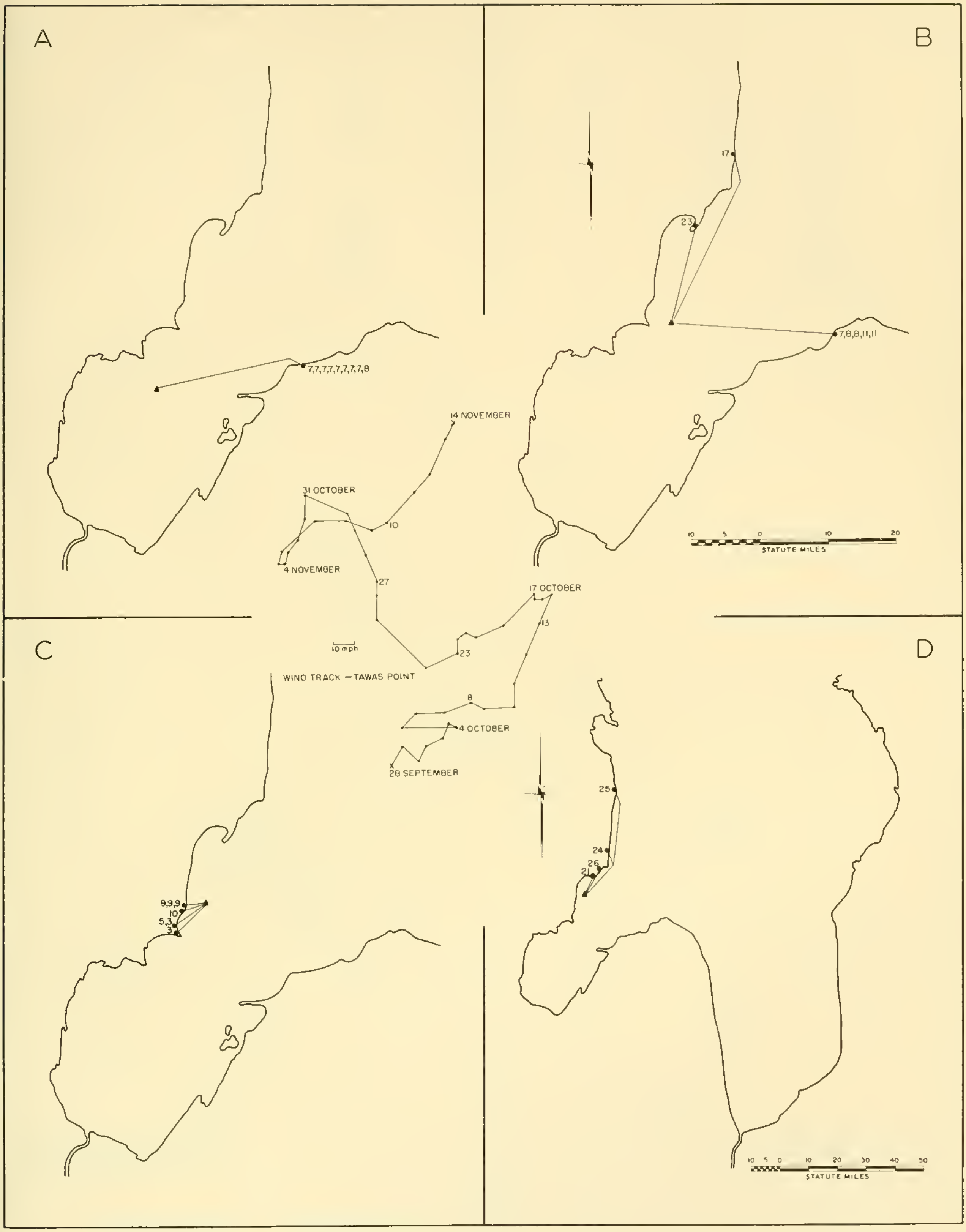

Figure 61.--Recovery points of drift bottles released October 3, 1956.

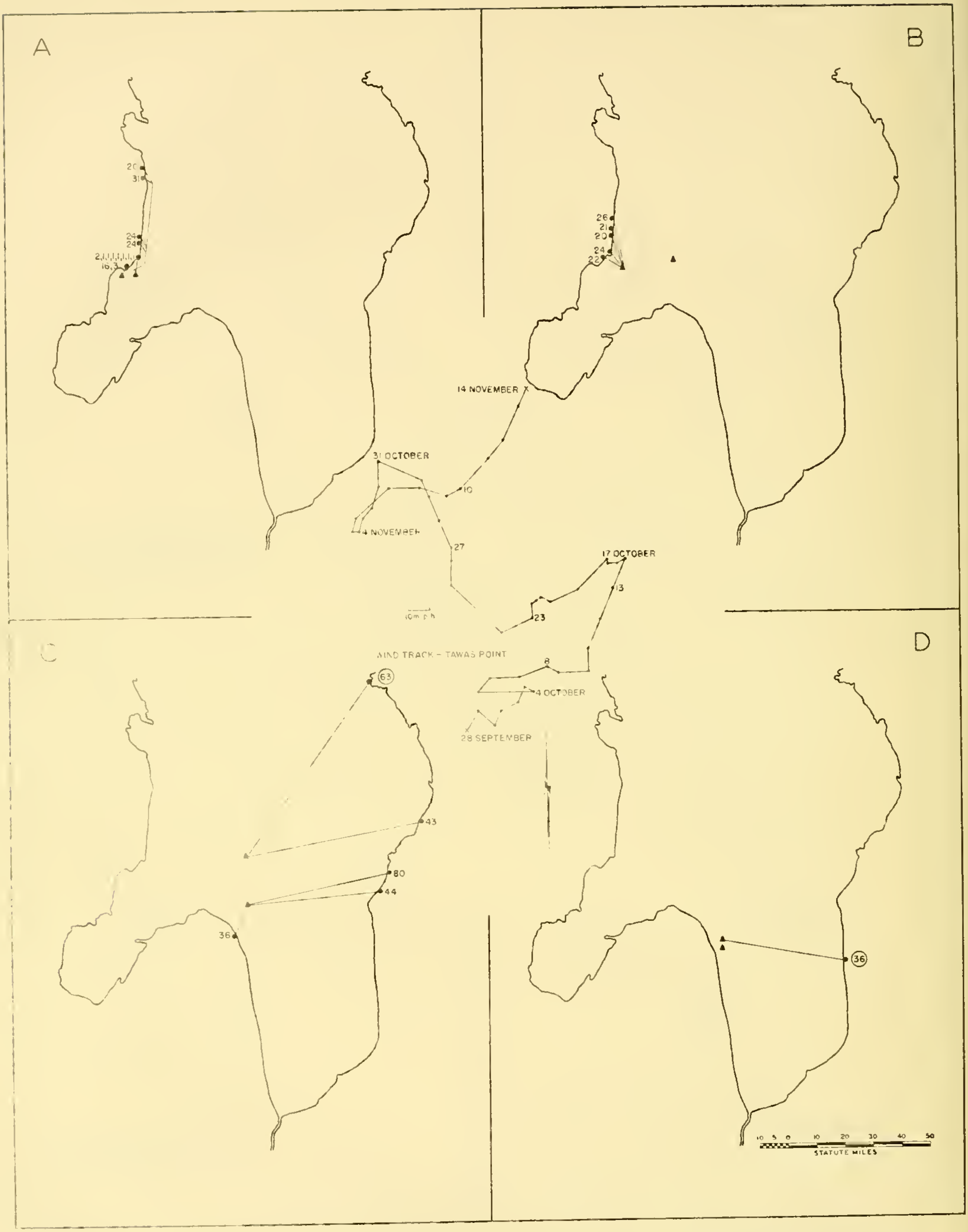

Figure 62.--Recovery points of drift bottles released October 4, 5, 1956.

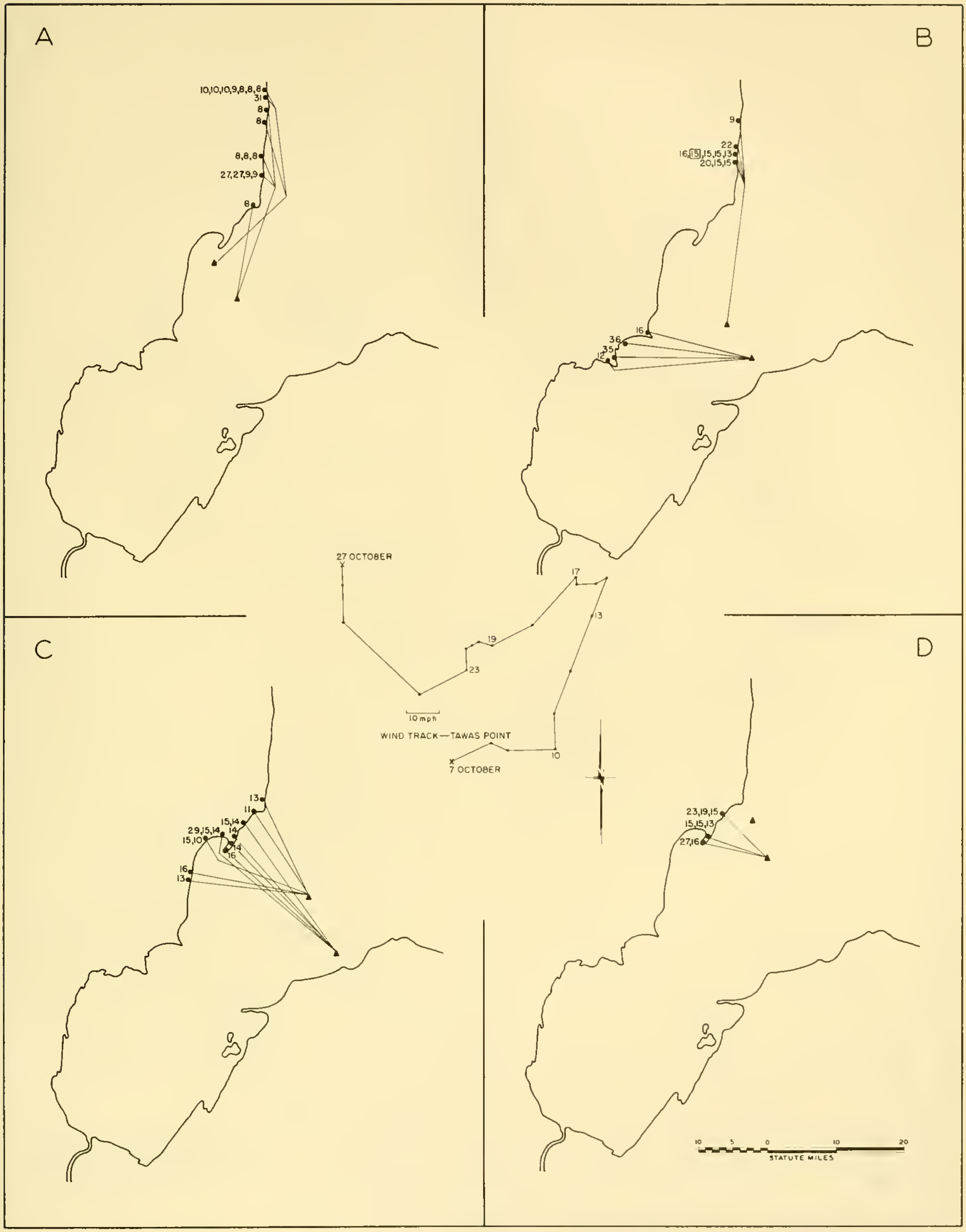

Figure 63.--Recovery points of drift bottles released October 12, 1956.

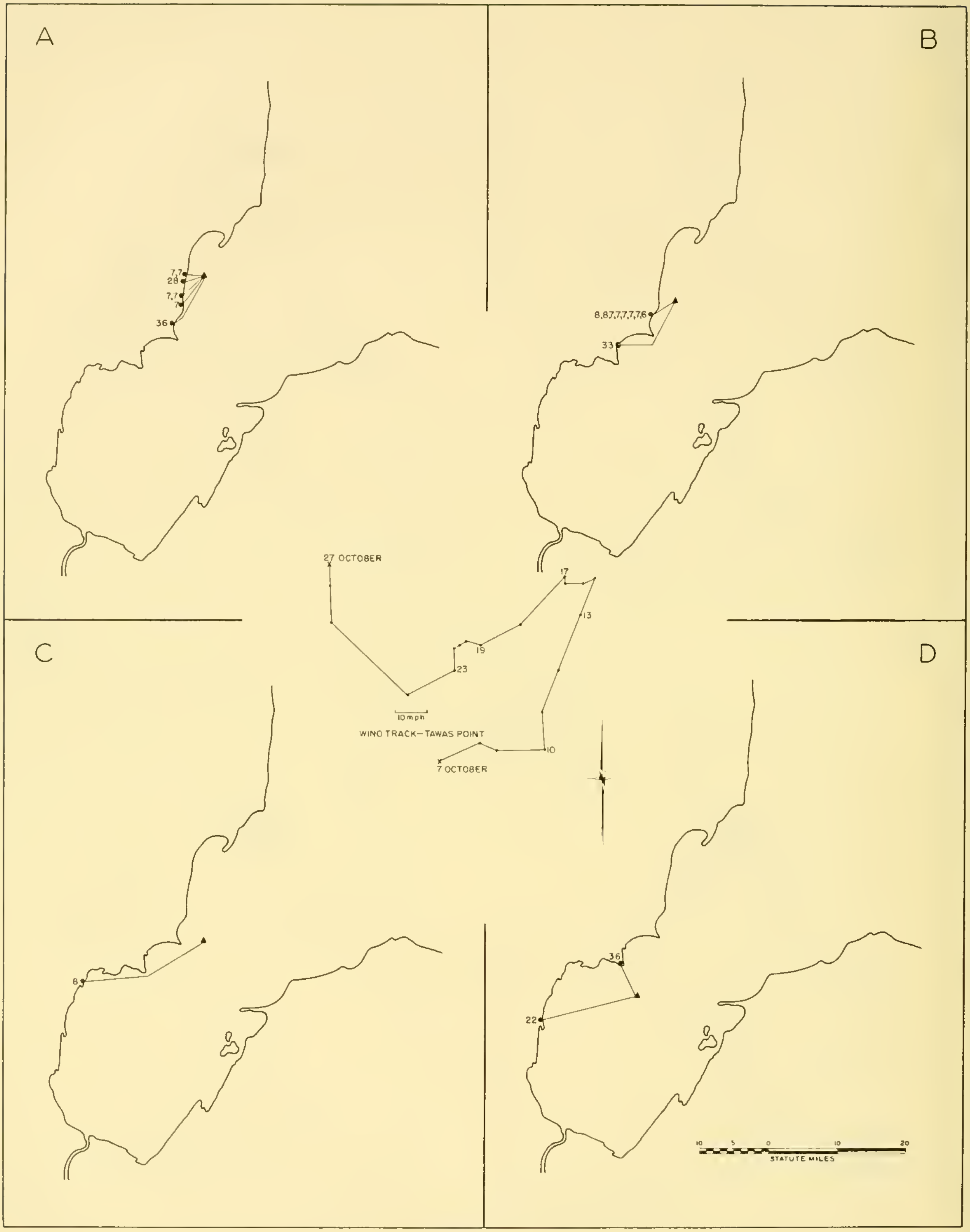

Figure 64.--Recovery points of drift bottles released October 13, 1956.

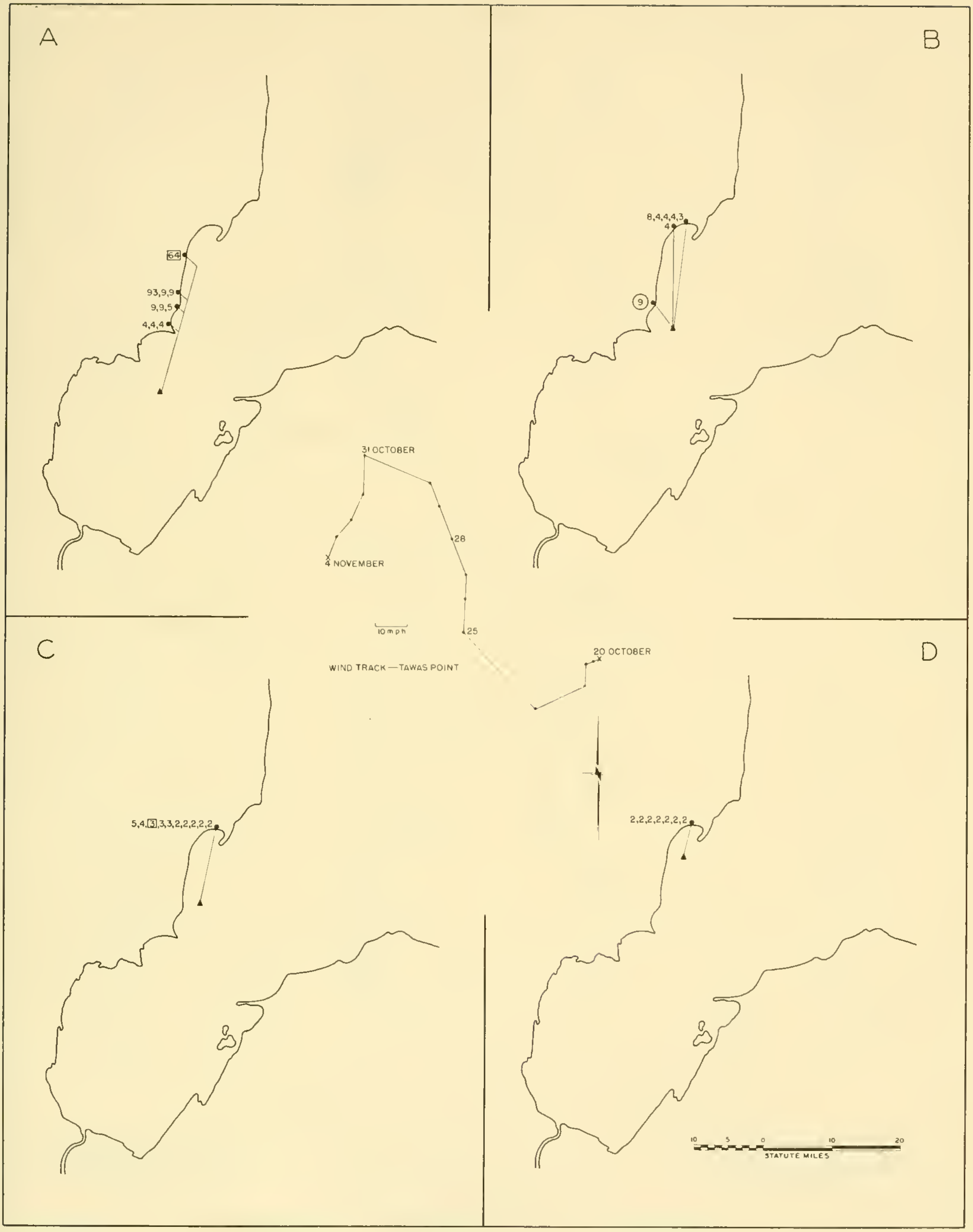

Figure 65.--Recovery points of drift bottles released October 25, 1956.

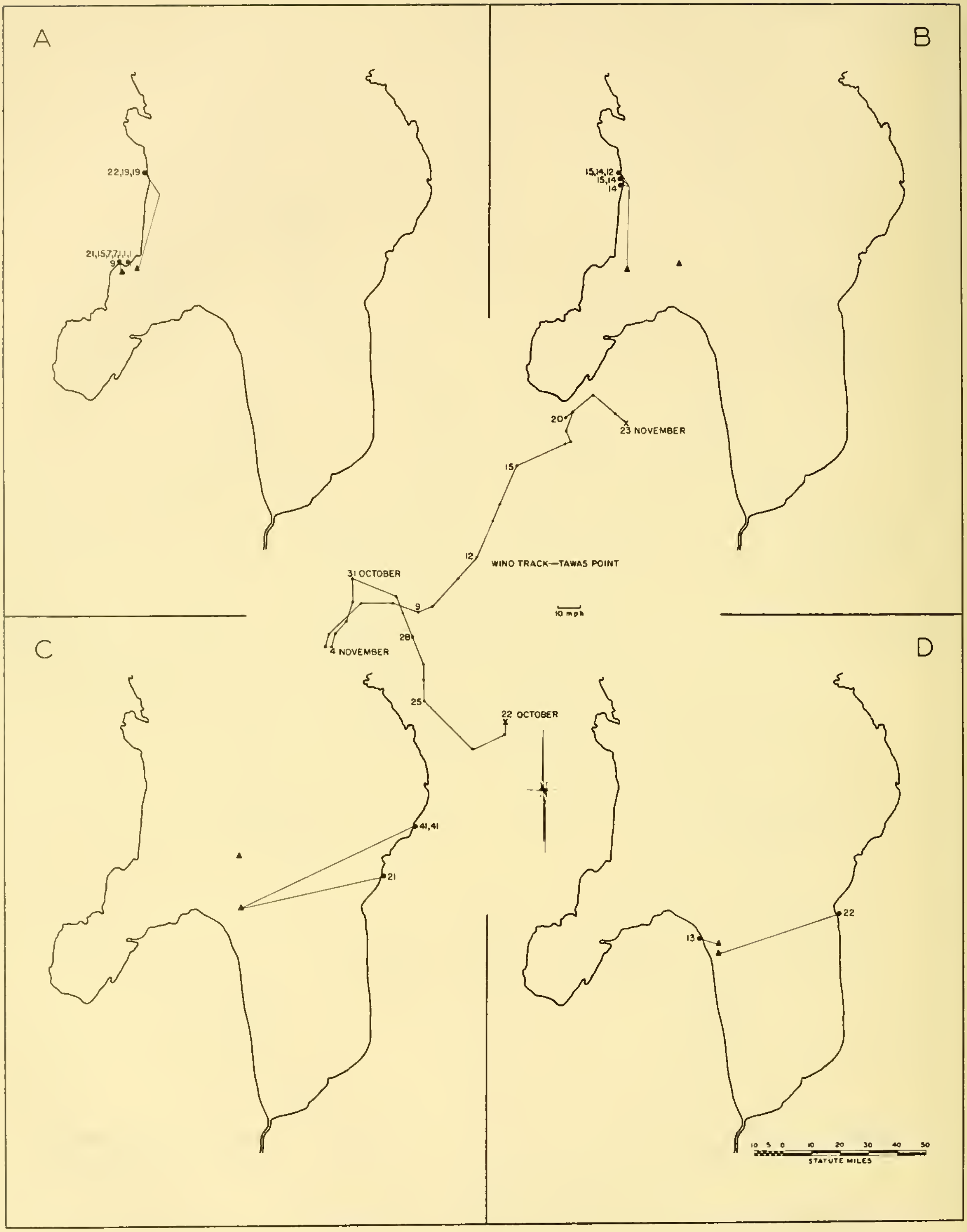

Figure 66.--Recovery points of drift bottles released October 27, 1956.

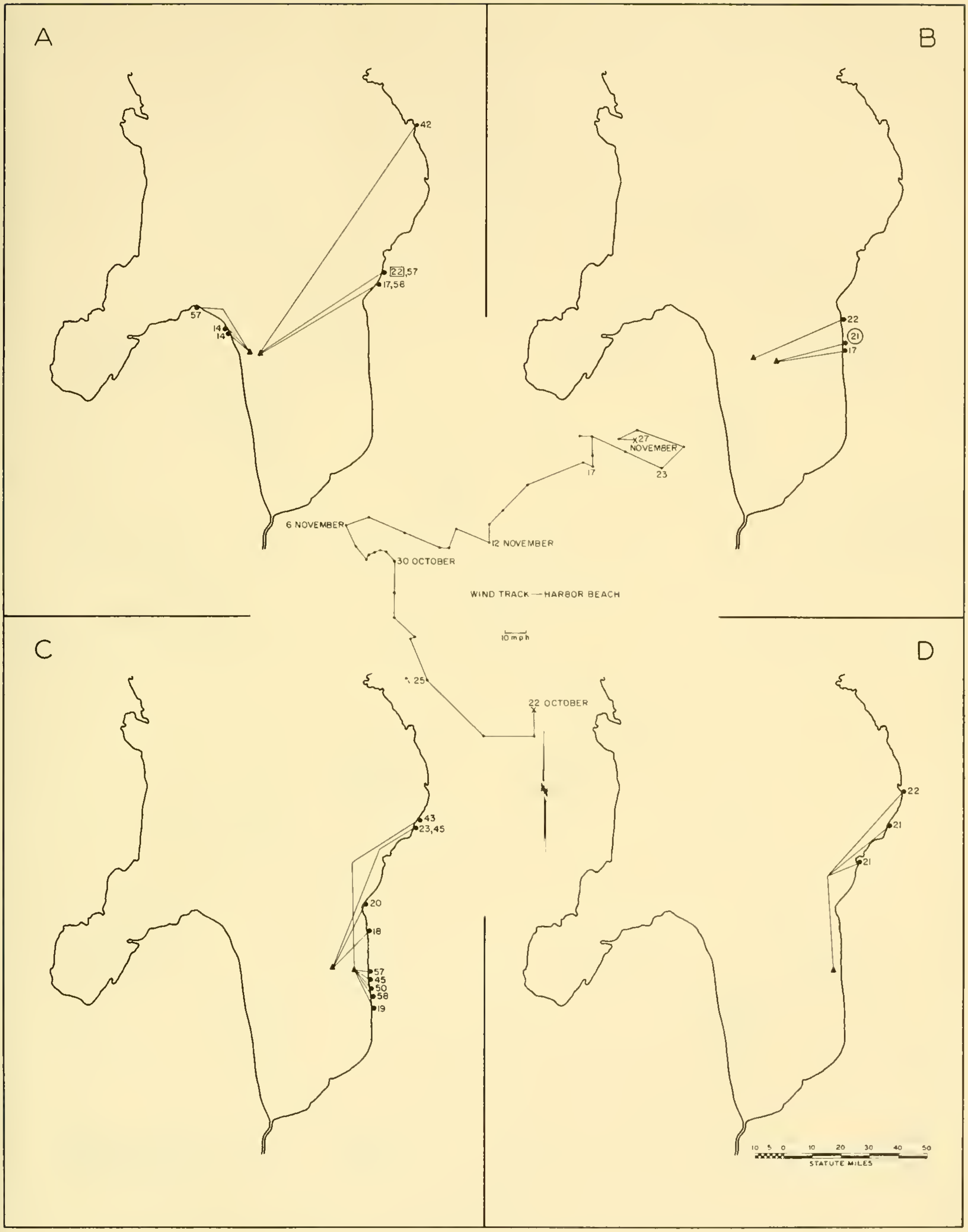

Figure 67.--Recovery points of drift bottles released October 27, 1956.

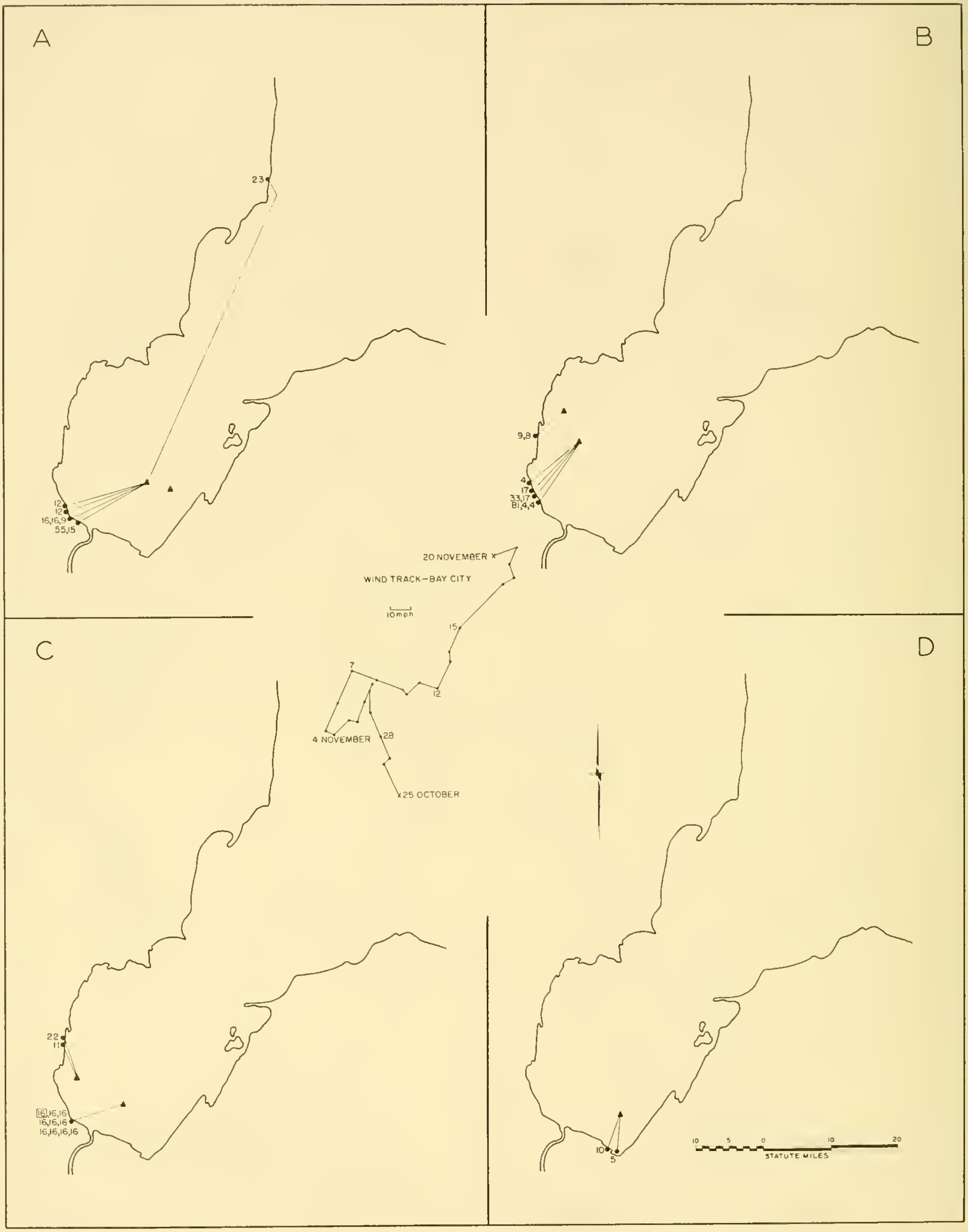

Figure 68.--Recovery points of drift bottles released October 30, 1956.

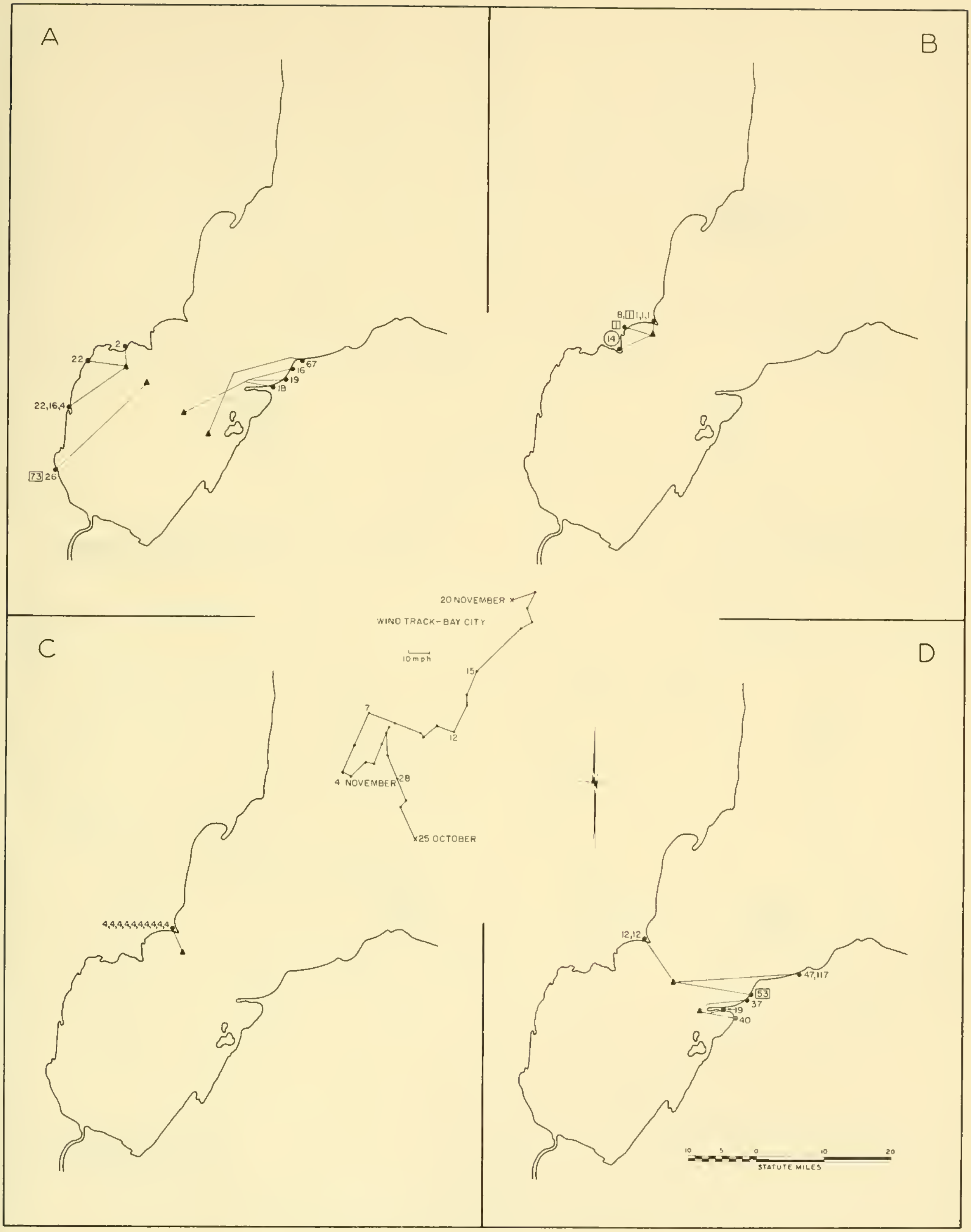

Figure 69.--Recovery points of drift bottles released October 30, 1956.

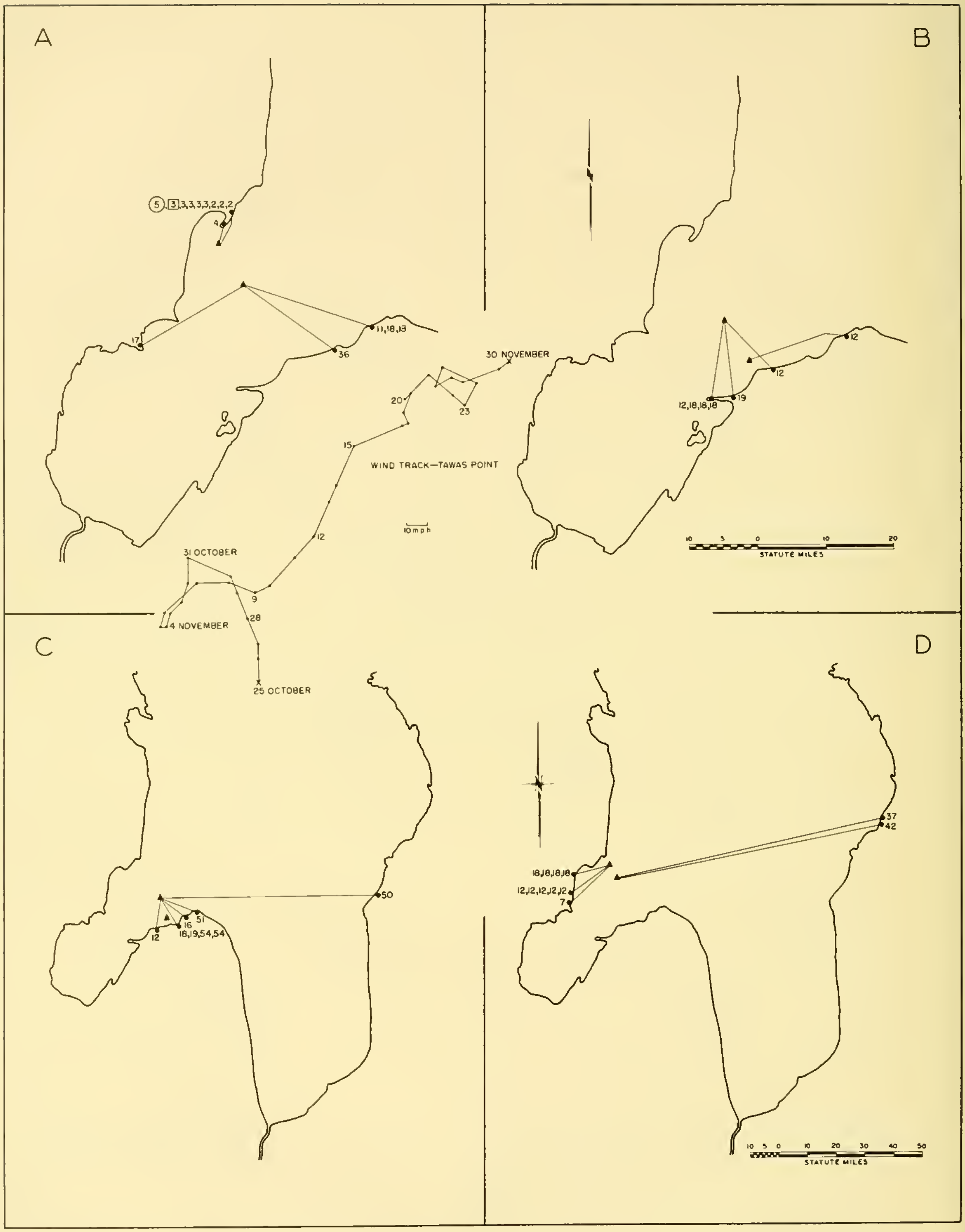

Figure 70.--Recovery points of drift bottles released October 30, 1956.

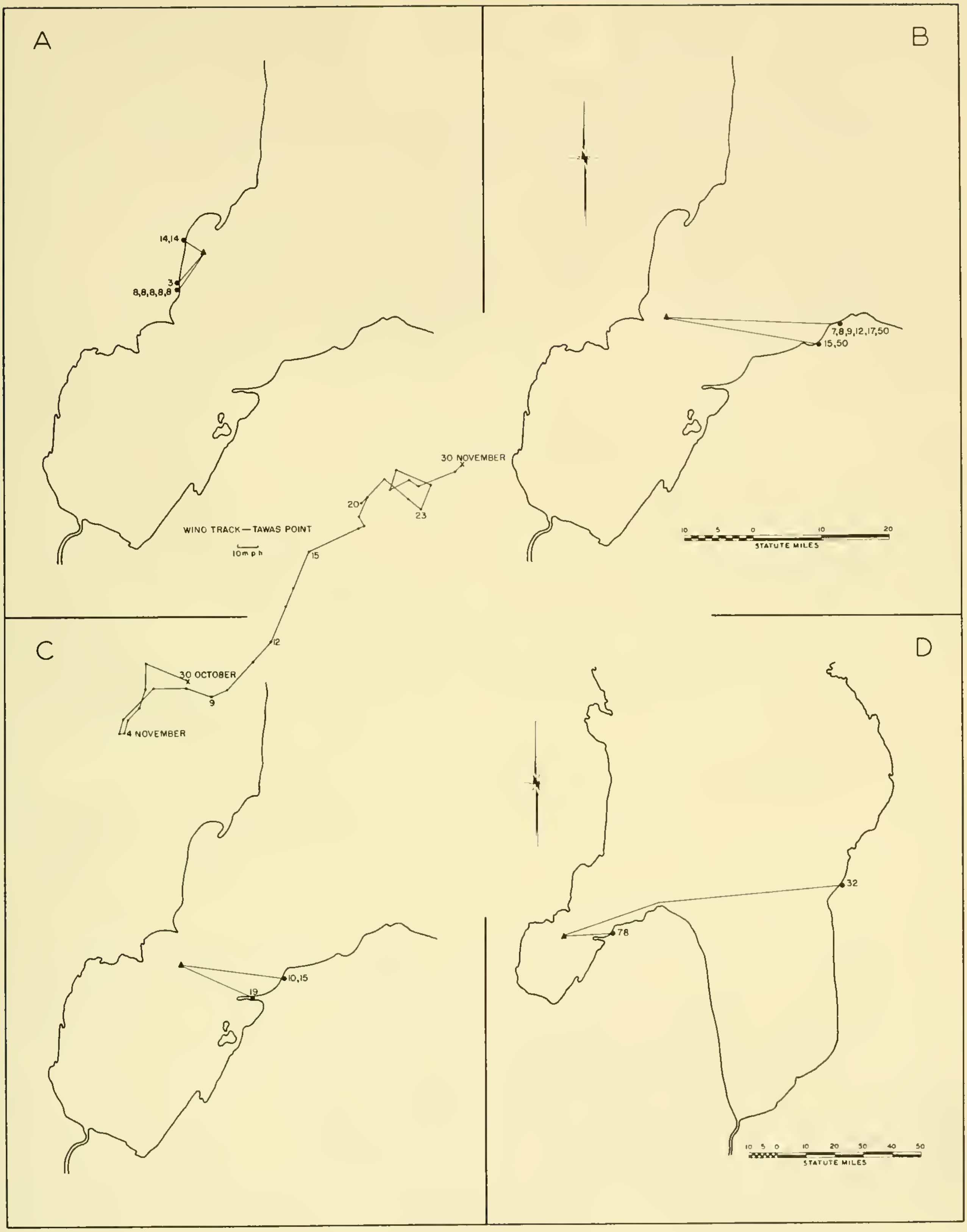

Figure 71.--Recovery points of drift bottles released November 3, 1956.

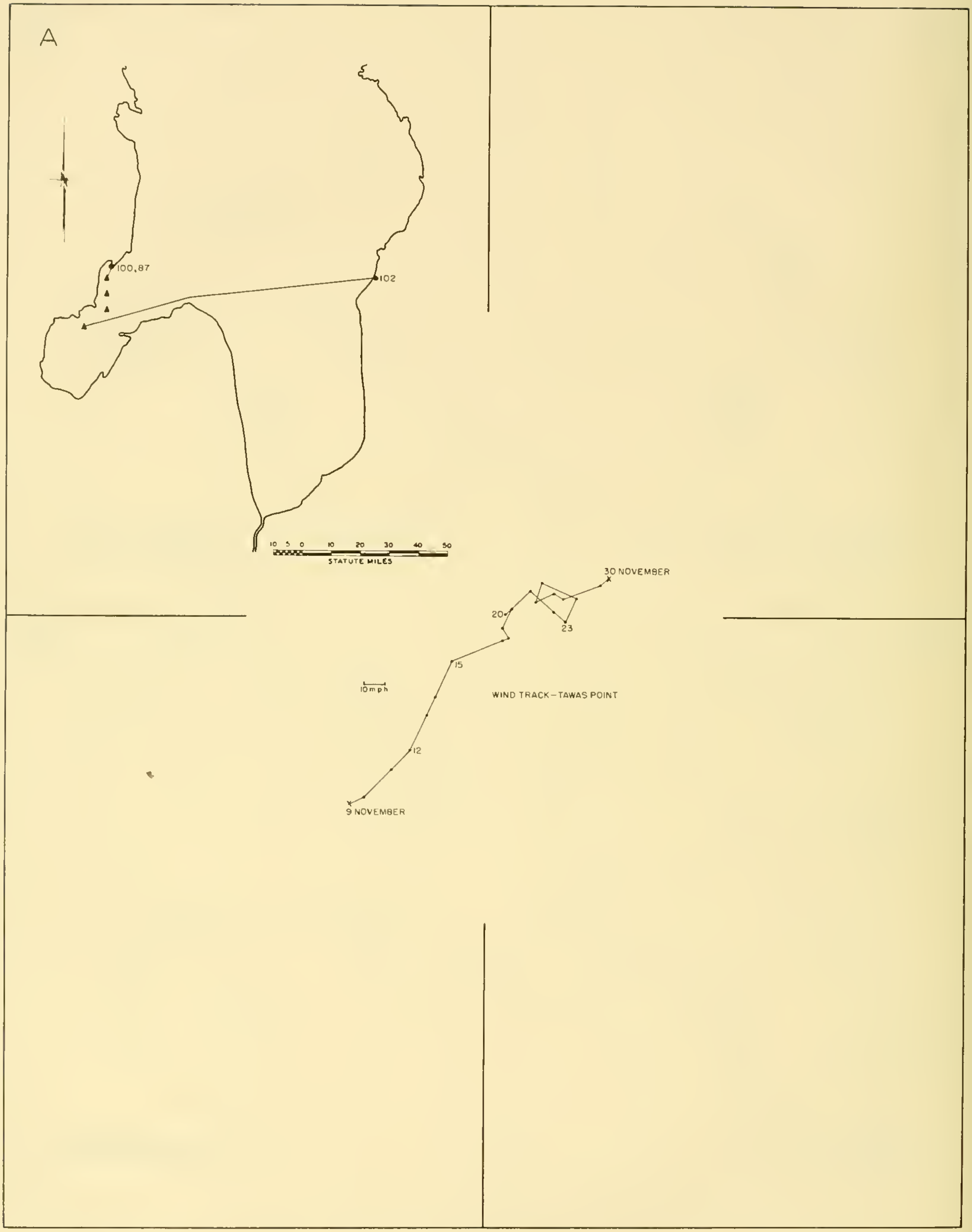

Figure 72.--Recovery points of drift bottles released November 14, 1956.

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