The Accumulated Sediment in Tippecanoe Lake and a Comparison with Winona Lake

IRA T. WILSON, Heidelberg College

1. Introduction

This paper, which describes the amount and distribution of the accumulated sediment in Tippecanoe Lake, is a sequel to a similar report made on Winona Lake (Wilson, 1936). A comparison of the two lakes is made, and some suggestions are offered to explain the distribution of the sediment.

The study is based upon 103 borings (Fig. 1) penetrating to the original bottom of the lake and distributed so that twelve cross section profiles (Fig. 2) could be made. A contour map of the original bottom (Fig. 3), constructed from the data, together with a 5-foot contour map of the present basin, formed the basis of the calculations of the volume of sediment.

Tippecanoe Lake contains three "marl islands" (Fig. 1). A study of these, together with that of two similar islands in Winona Lake, make it practically certain that the interpretation given in the report on Winona Lake is correct.

Chemical analyses of the samples of the sediment in the lake are being made. A report of this aspect of the work will be made in the near future by David F. Opdyke and the author.

2. Acknowledgments

The author is especially indebted to the late Dr. Will Scott, director of the Indiana University Biological Station, for suggesting and encouraging the work on Tippecanoe Lake and for furnishing the equipment to carry it on. Acknowledgment is due, also, to Mr. Bruce Pierce, who donated the use of his property and splendidly equipped boat, repair shop, and garage. Two students, David F. Opdyke and Frederick J. Ludwig, and the writer's son, Robert Wilson, helped in the field work. The author is indebted also to James H. Kranich, who has done much of the work on the maps and the calculations contained in the tables. The writer's faculty colleagues, Dr. Jesse Pierce and Professor G. A. Stinchcomb, have discussed the technique of the study of the data with him many times and have made many useful suggestions.

3. General Description of Tippecanoe Lake

Tippecanoe Lake is located in Kosciusko County, Indiana, about 10 miles northeast of Warsaw. It lies in sections 1, 11, 12, T. 33 N., R. 6 E, and sections 6-9, 16-18, T. 33 N., R. 7 E. By interpolation of a description by Leverett (1915, pp. 138, 140), it seems that the lake lies on the outer border of the east end of the New Paris moraine of the Saginaw lobe, near the union of this moraine with the Pakerton moraine (Malott, 1922, p. 118). A broad gravel plain extending from the west end of the lake several miles is apparently outwash from the New Paris moraine. The lake is long and narrow with high (20-40 feet) ridges along each side. This fact caused Blatchley and Ashley

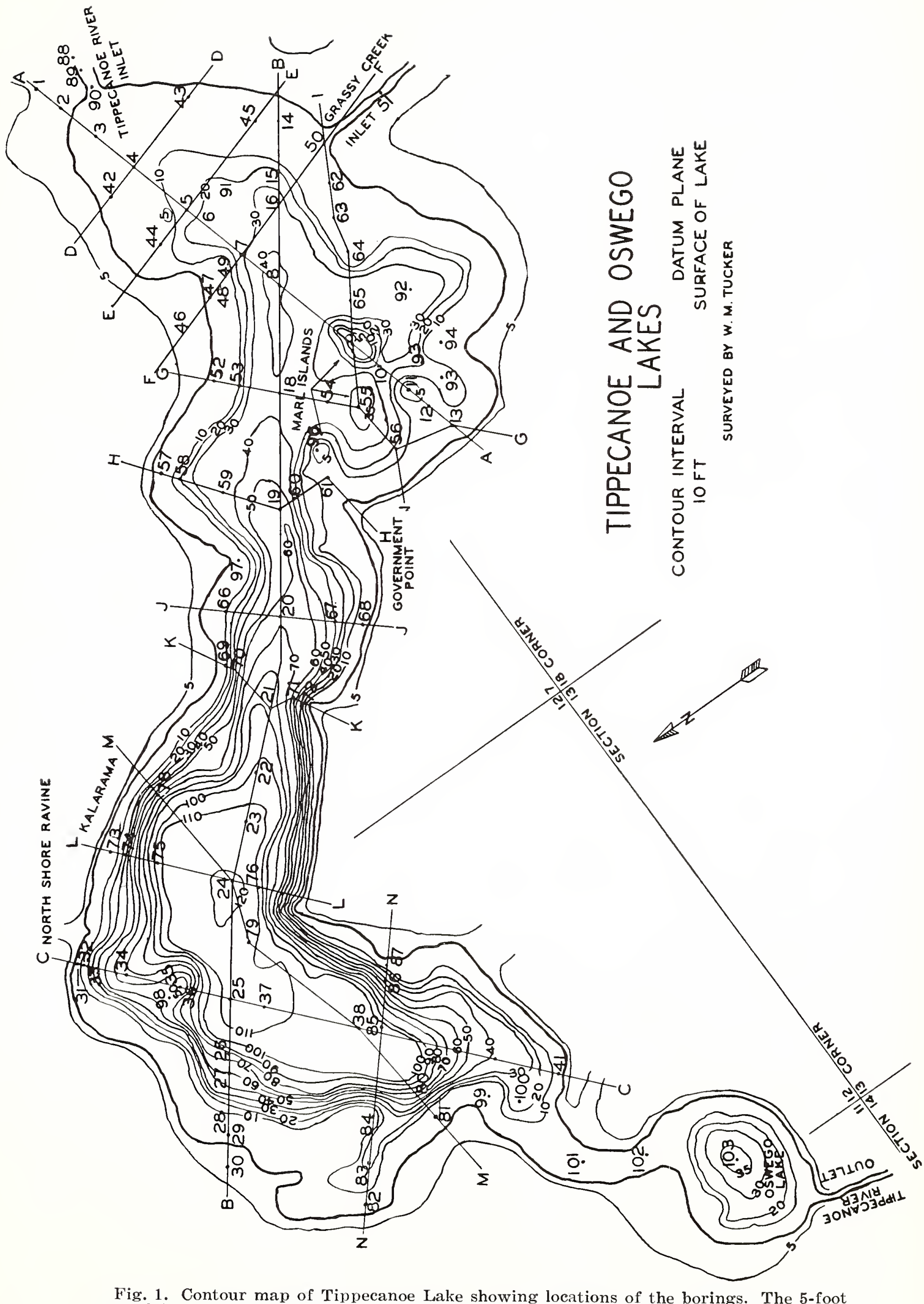


Fig. 1. Contour map of Tippecanoe Lake showing locations of the borings. The 5-foot contour lying outside the shore is assumed to be the original lake shore. (Note the following errata in cut: boring No. 39 should be inserted on CC at contour 80 and 77 on LL at contour 40; No. 93 should be 95.)

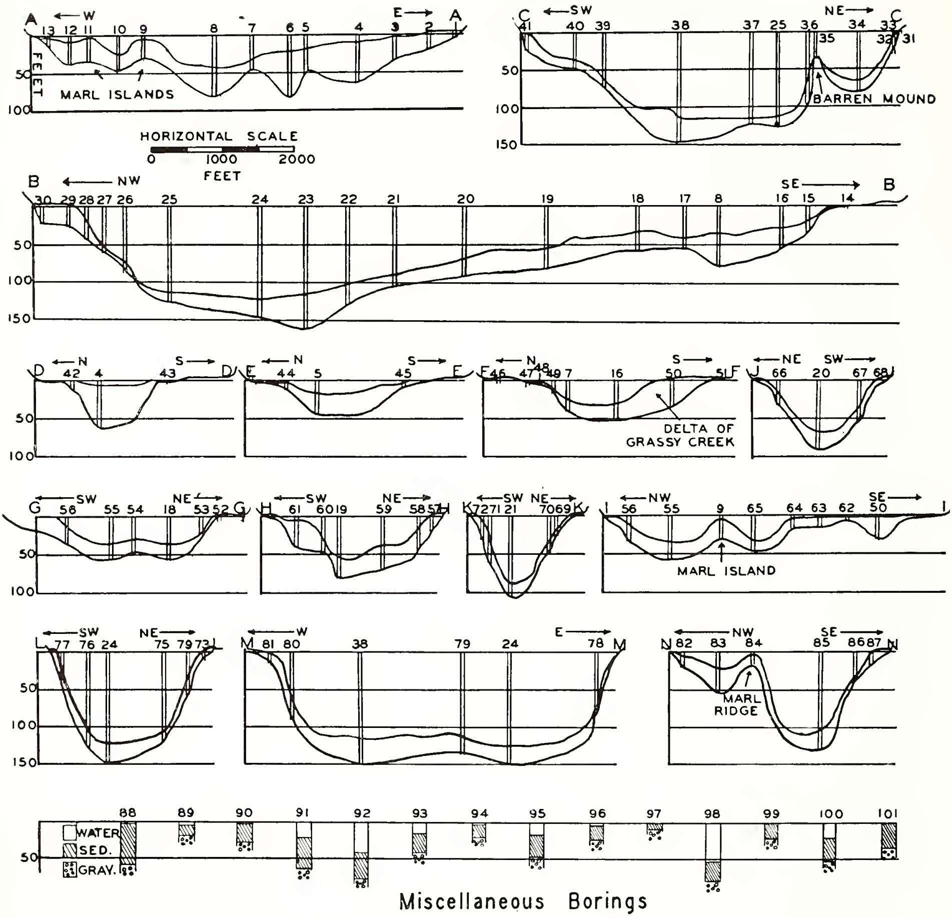


Fig. 2. Profile diagrams of the original (lower line) and the present lake basins (upper lines). The space between the lines represents the sediment in the lake. The vertical scale of the diagrams is ten times the horizontal. Borings are shown as double vertical lines and are numbered as in Figure 1. (No. 79 in profile LL should be 74.)

(1900, p. 35) to classify Tippecanoe as a channel lake, but it seems more likely that it is of the kettle-hole type lying in the outwash plain.

The greatest present depth of the lake is 123 feet; it is the deepest lake in the state. Its present basin has an area of 707 acres. There are two inlets (Tippecanoe River and Grassy Creek) and one outlet. Since both entering streams drain large morainic areas containing many lakes and swamps and are interrupted in their courses many times by lakes, they have a relatively constant and regular flow and carry a very light load of sediment. Fluctuations of 4 feet in the level have been reported by local residents.

The thermocline on August 12, 1912, was between 20 and 30 feet as inferred from a temperature series reported by Scott (1916, p. 25). The pH of the bottom water was 7.2 on July 12, 1937.

The elongated shape of the lake, its great depth, and its position in the main channel of the river, with a narrow shelf zone at the deep west end and a broad shelf zone at the shallow east end (Fig. 1), made it seem likely, at the outset of the work, that this would be a good basin for comparison with Winona Lake already studied. The latter lake has about the same area but is more nearly circular and less diversified in the shape of the basin; like Tippecanoe Lake it has two inlets and one outlet, but it is not in the main channel of a river. Winona Lake has a much smaller drainage area than Tippecanoe Lake, but its entering streams have been relatively less interrupted by flowing through other lakes. Both have their long axes in the direction of the prevailing winds. The original shore line of Winona Lake is 5.1 miles (.000777 ft. per sq. ft. of area) as compared with 6.8 miles (.000923 ft. per sq. ft.) for Tippecanoe Lake.

All the sediment in Tippecanoe Lake is marl except a thin layer over the emerged zones between the original and present shores, which is peat. Blatchley and Ashley (1900, p. 194) report as an average sample along the south shore near Government Point the following analysis:

Calcium carbonate ($CaCO_3$)	91.02%
Magnesium carbonate ($MgCO_3$)	2.28%
Iron oxide (Fe_2O_3)	0.29%
Calcium sulphate ($CaSO_4$)	0.05%
Insoluble (Silica, etc.)	2.92%
Organic matter	2.10%

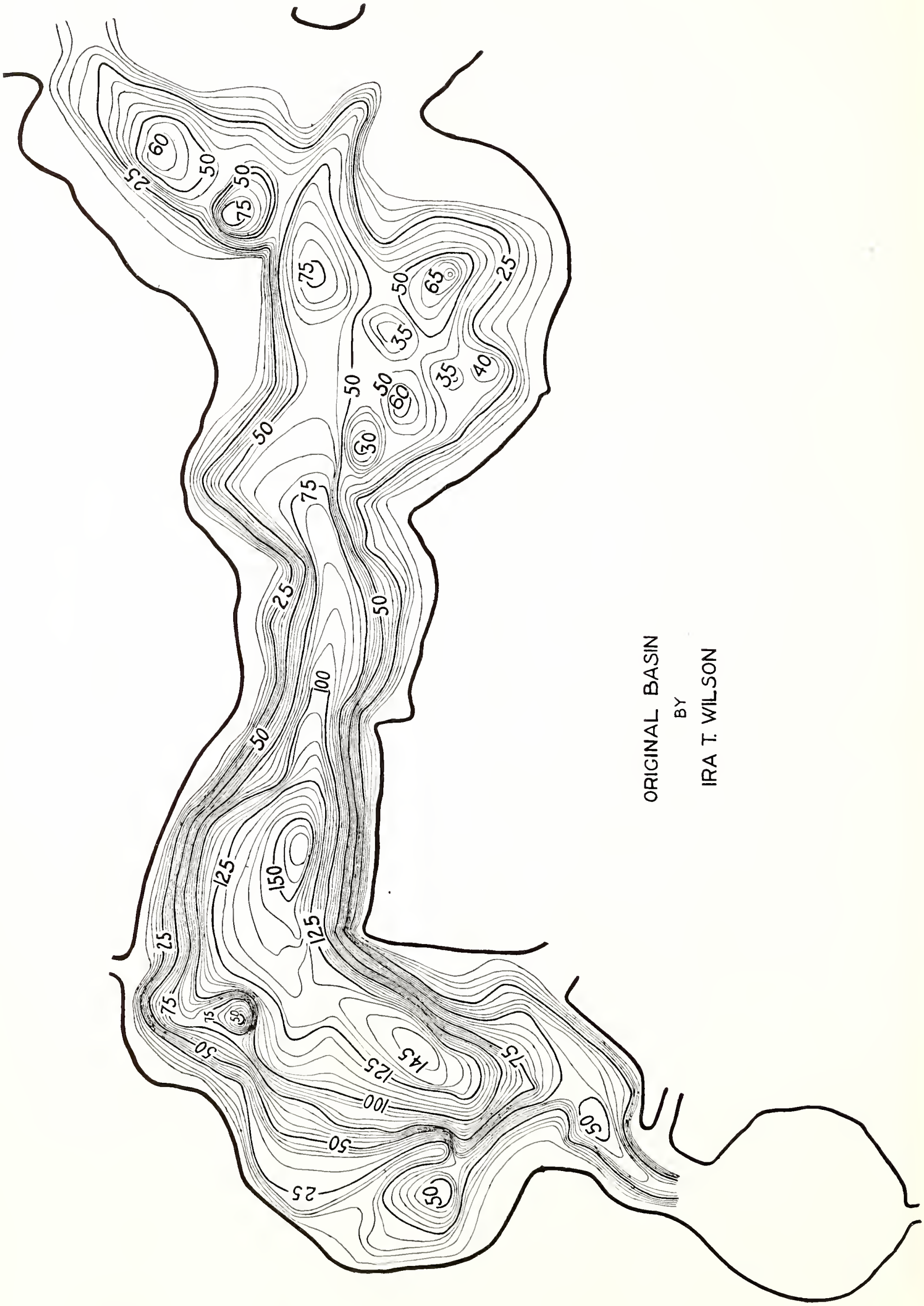
The writer's analyses of samples near shore agree with this generally but show much less carbonate (below 50%) and more silica (over 50%) in the deep water.

4. Method of Study

The method used to locate the positions of the borings (Fig. 1); the description of the boring apparatus and its use; the method of sampling, of keeping field notes, of constructing the profile diagrams and contour maps of the original bottom, and the calculation of the volume of sediment are the same as those already described in the report of the work on Winona Lake (Wilson, 1936, p. 296).

The calculations of volumes were made separately for the 3 sections (A, B, C, Fig. 3) of the lake. This was done in order to make comparisons between different parts of the basin, as section A is deep, section C shallow, and sectionl B intermediate.

In determining the hypothetical 50-percentile contours (p. 243) the following method was used: the bottom of the frustrum above and below which 50% of the sediment of the basin lies was determined by consulting tables (Tables I, II, III, and IV) which give the volume of sediment by frustra. The 50-percentile contour (i.e., the contour which, when projected vertically through the sediment, divides the sediment of the basin so that 50% lies outside and 50% inside it) lies between the contour lines of the original and present basin which fall in the base of the frustrum in question. For the purpose of study the contour



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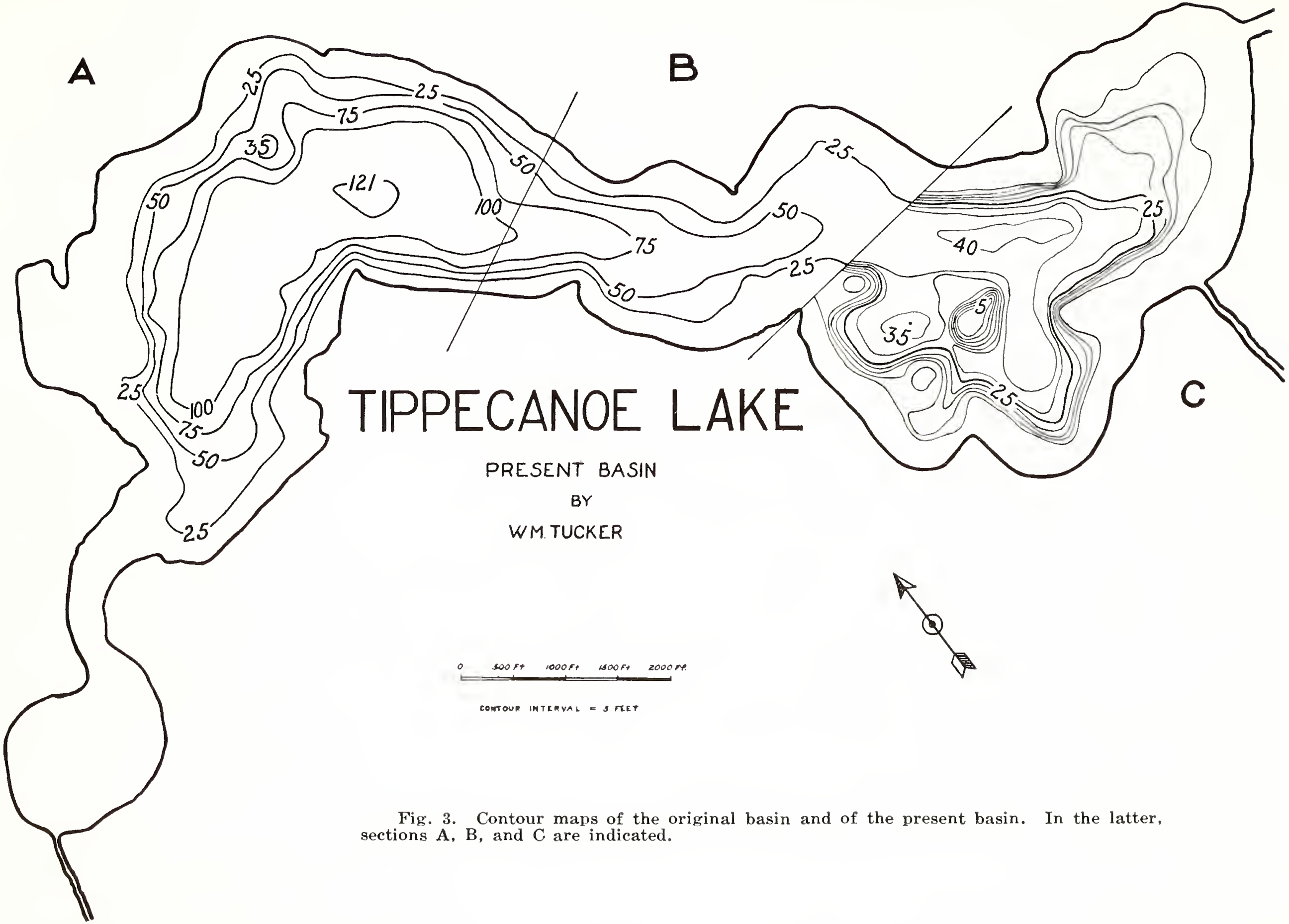

Fig. 3. Contour maps of the original basin and of the present basin. In the latter, sections A, B, and C are indicated.

TABLE I.—Volumes in cubic feet of the sediment in the frustra of Tippencanoe Lake when the lake is regarded as a cone divided into frustra by the contours of the original and present basins. The figures in the column "Volume of Sediment" represent totals of the corresponding columns in Tables II, III, and IV.

	Depth of Frustra (Feet)	Volume of Sediment	Total to Level	Percentage of Total Volume of Sediment
1.	0– 5	37,700,000	37,700,000	6.91
2.	5– 10	32,498,500	70,198,500	12.87
3.	10– 15	36,488,000	106,686,500	19.56
4.	15– 20	33,500,000	140,186,500	25.69
5.	20– 25	31,900,000	172,086,500	31.56
6.	25– 30	31,360,000	203,446,500	37.29
7.	30– 35	32,128,000	235,574,500	43.19
8.	35– 40	34,256,000	269,830,500	49.46
9.	40– 45	34,432,000	304,262,500	55.78
10.	45– 50	28,348,000	332,610,500	60.97
11.	50– 55	22,491,000	355,101,500	65.10
12.	55– 60	19,177,000	374,278,500	68.61
13.	60– 65	15,888,500	390,167,000	71.52
14.	65– 70	12,378,500	402,545,500	73.79
15.	70– 75	10,504,000	413,049,500	75.72
16.	75– 80	8,688,000	421,737,500	77.31
17.	80– 85	7,770,000	429,507,500	78.74
18.	85– 90	6,777,500	436,285,000	79.98
19.	90– 95	6,281,500	442,566,500	81.13
20.	95– 100	6,280,000	448,846,500	82.28
21.	100– 105	7,288,000	456,134,500	83.62
22.	105– 110	9,980,000	466,114,500	85.45
23.	110– 115	12,931,000	479,045,500	87.82
24.	115– 120	15,159,000	494,204,500	90.60
25.	120– 125	15,384,000	509,588,500	93.42
26.	125– 130	12,828,000	522,416,500	95.77
27.	130– 135	9,660,000	532,076,500	97.54
28.	135– 140	6,492,000	538,568,500	98.73
29.	140– 145	3,832,000	542,400,500	99.43
30.	145– 150	1,896,000	544,296,500	99.78
31.	150– 155	828,000	545,124,500	99.93
32.	155– 160	392,000	545,516,500	100.00

need be only hypothetical since the areas and volumes of sediment can be determined without locating the contours on the map. The area inside the 50-percentile contour was determined specifically by the following formula:

$$A = \frac{a_1 + a_2}{2}$$

where A is the area inside the 50-percentile contour, a_1 the area of the present basin that falls in the base of the frustrum, and a_2 the area within the contour of the original basin that falls in the base of the frustrum. The area outside the 50-percentile contour is determined by subtracting A from the total area of the original basin. The areas outside and inside the other percentile contours were determined by a similar method except that the base of the frustrum above and below which the desired percentages of the sediment lies was used as the basis of the calculations.

TABLE II.—Volumes in cubic feet of the sediment in the frustra of section A of Tippecanoe Lake when section A is regarded as a cone divided into frustra by the contours of the original and present basins.

	Depth of Frustra	Volume of Sediment	Total to Level	Percentage of Total Volume Of Sediment
1.	0– 5	11,284,000	11,284,000	4.81
2.	5– 10	10,375,500	21,659,500	9.24
3.	10– 15	14,012,000	35,671,500	15.22
4.	15– 20	12,092,000	47,763,500	20.37
5.	20– 25	11,060,000	58,823,500	25.09
6.	25– 30	9,556,000	68,379,500	29.17
7.	30– 35	8,000,000	76,379,500	32.58
8.	35– 40	7,328,000	83,707,500	35.71
9.	40– 45	6,724,000	90,431,500	38.58
10.	45– 50	5,476,000	95,907,500	40.91
11.	50– 55	4,680,000	100,587,500	42.91
12.	55– 60	4,460,000	105,047,500	44.81
13.	60– 65	4,728,000	109,775,500	46.83
14.	65– 70	4,680,000	114,455,500	48.83
15.	70– 75	4,396,000	118,851,500	50.70
16.	75– 80	4,120,000	122,971,500	52.50
17.	80– 85	4,120,000	127,091,500	54.22
18.	85– 90	4,213,500	131,305,000	56.01
19.	90– 95	4,289,500	135,594,500	57.84
20.	95– 100	4,640,000	140,234,500	59.81
21.	100– 105	6,048,000	146,282,500	62.40
22.	105– 110	9,248,000	155,530,500	66.35
23.	110– 115	12,572,000	168,102,500	71.71
24.	115– 120	15,000,000	183,102,500	78.11
25.	120– 125	15,384,000	198,486,500	84.67
26.	125– 130	12,828,000	211,314,500	90.10
27.	130– 135	9,660,000	220,974,500	94.22
28.	135– 140	6,492,000	227,466,500	97.04
29.	140– 145	3,832,000	231,298,500	98.67
30.	145– 150	1,896,000	233,194,500	99.48
31.	150– 155	828,000	234,022,500	99.83
32.	155– 160	392,000	234,414,500	100.00

5. Description and Discussion of Findings

A. Description of the Maps

Figure 1 shows a contour map of Tippecanoe Lake with the locations of the 103 borings that were made. The details of the depths of water and sediment found at any boring can be ascertained by referring to the profile diagrams (Fig. 2). The profiles are located along the lines A-A, B-B, etc., on Figure 1, and have lettering and boring numbers corresponding to them. The water level has been the point of reference in the construction of all the profile diagrams.

B. Morphometry of the Original Basin

The original bottom of the lake was very uneven due to the presence of many ridges and knobs with intervening troughs and basins (Figs. 2 and 3). In fact, 10 sub-basins, at borings 4, 6, 8, 23, 38, 55, 83, 92, 95, and 100, can be identified on the original bottom. The sub-basin

TABLE III.—Volumes in cubic feet of the sediment in the frustra of section B of Tippecanoe Lake when section B is regarded as a cone divided into frustra by the contours of the original and present basins.

	Depth of Frustra	Volume of Sediment	Total to Level	Percentage of Total Volume of Sediment
1.	0– 5	5,244,000	5,244,000	5.79
2.	5– 10	4,039,000	9,283,000	10.26
3.	10– 15	3,860,000	13,143,000	14.52
4.	15– 20	3,644,000	16,787,000	18.55
5.	20– 25	3,352,000	20,139,000	22.26
6.	25– 30	3,320,000	23,459,000	25.93
7.	30– 35	3,532,000	26,991,000	29.83
8.	35– 40	4,272,000	31,263,000	34.55
9.	40– 45	5,436,000	36,699,000	40.56
10.	45– 50	5,984,000	42,683,000	47.18
11.	50– 55	6,131,000	48,814,000	53.95
12.	55– 60	7,053,000	55,867,000	61.75
13.	60– 65	6,852,500	62,719,500	69.32
14.	65– 70	5,666,500	68.386,000	75.58
15.	70– 75	5,188,000	73,574,000	81.32
16.	75– 80	4,568,000	78,142,000	86.37
17.	80– 85	3,650,000	81,792,000	90.40
18.	85– 90	2,564,000	84,356,000	93.24
19.	90– 95	1,992,000	86,348,000	95.44
20.	95– 100	1,640,000	87,988,000	97.25
21.	100– 105	1,240,000	89,228,000	98.62
22.	105– 110	732,000	89,960,000	99.43
23.	110– 115	359,000	90,319,000	99.83
24.	115– 120	159,000	90,478,000	100.C0

TABLE IV.—Volumes in cubic feet of the sediment in the frustra of section C of Tippecanoe Lake when section C is regarded as a cone divided into frustra by the contours of the original and present basins.

	Depth of Frustra	Volume of Sediment	Total to Level	Percentage of Total Volume Sediment
1.	0– 5	21,172,000	21,172,000	9.59
2.	5– 10	18,084,000	39,256,000	17.79
3.	10– 15	18,616,000	57,872,000	26.23
4.	15– 20	17,764,000	75,636,000	34.28
5.	20– 25	17,488,000	93,124,000	42.21
6.	25– 30	18,484,000	111,608,000	50.59
7.	30– 35	20,596,000	132,204,000	59.92
8.	35– 40	22,656,000	154,860,000	70.19
9.	40– 45	22,272,000	177,132,000	80.29
10.	45– 50	16,888,000	194,020,000	88.25
11.	50– 55	11,680,000	205,700,000	93.23
12.	55– 60	7,664,000	213,364,000	96.71
13.	60– 65	4,308,000	217,672,000	98.29
14.	65– 70	2,032,000	219,704,000	99.58
15.	70– 75	920,000	220,624.000	100.00

TABLE V.—Tabulation of data, some of which appear in Tables I, II, III, and IV, some are taken from the publication on Winona Lake (Wilson, 1936), but are transposed to feet, and some are new, being based on calculations the details of which are not included. The areas inside and outside the 50-percentile contours of Winona Lake and therefore, the other figures based on them, as recorded here, were calculated on the same basis as the corresponding figures for Tippecanoe Lake and differ from those previously published to a slight extent since the method used for Tippecanoe Lake (p. 000) differs slightly from that used for Winona Lake.

	Area of Original Basin (Square feet)	Area of Present Basin	Area of Original Basin Obliterated	Percentage of Basin Obliterated	Volume of the Original Basin (Cubic feet)	Volume of the Present Basin	Volume of Sediment	Percentage of Basin filled with Sediment	Area outside 50-percentile Contour
Winona	35,033,182	21,919,497	13,113,685	37.4	1,197,561,103	674,576,537	522,924,566	43.66	22,571,811
Tippecanoe as a whole	39,070,400	30,934,400	8,136,000	20.82	1,707,404,500	1,161,888,000	545,516,500	31.90	24,879,200
Tippecanoe—Sec. A	15,726,400	13,804,800	1,921,600	12.22	1,014,407,500	779,993,000	234,414,500	23.10	9,804,000
Tippecanoe—Sec. B	6,969,600	5,796,800	1,172,800	16.82	292,361,000	201,883,000	90,478,000	30.90	4,584,000
Tippecanoe—Sec. C	16,374,400	11,332,800	5,041,600	30.78	400,636,000	180,012,000	220,624,000	55.00	12,279,200

	Percentage of area of Original Basin outside 50-percentile Contour	Average depth of Sediment outside 50-percentile Contour	Area inside 50-percentile Contour	Percentage of Area inside 50-percentile Contour	Average Depth of Sediment inside 50-percentile Contour	Ratio of rate of Sediment Accum. inside and outside 50-percentile Contour	Area of Original Basin outside 20-foot Contour	Percentage of Area outside 20-foot Contour	Cu. Ft. of Total Sediment per Sq. Ft. of Area outside 20-foot Contour	Average Depth of Sediment
Winona	64.42	11.58	12,461,371	35.58	20.98	1.81	16,090,432	45.9	32.50	14.92
Tippecanoe as a whole	63.68	10.96	14,191,200	36.32	19.22	1.75	18,377,600	47.0	29.67	13.96
Tippecanoe—Sec. A	62.34	11.96	5,922,400	37.66	19.79	1.65	5,248,000	33.4	44.66	14.91
Tippecanoe—Sec. B	65.80	9.87	2,385,600	34.2	18.96	1.92	2,966,400	42.6	30.50	14.98
Tippecanoe—Sec. C	75.00	8.98	4,095,200	25.05	26.94	3.00	10,163,200	62.1	21.71	13.47
Total	....	....	12,403,200 (Sum of Parts)							

at boring 23 was 164 feet deep originally, whereas that at boring 95 was only 43 feet deep.

Four prominent knobs occurring on the original bottom are of special significance since three of them support the three "marl islands" (Figs. 1, 2, and 3). The fourth knob, "barren mound" (Figs. 1 and 2), rises 40 feet above the surrounding level. The uneven form of the original bottom with knobs, ridges, and intervening depressions, is more suggestive of rolling morainic topography than of a glacial river channel.

C. The Distribution of the Sediment

The profile diagrams (Fig. 2) show that the sediment is distributed over nearly the entire original bottom except on the barren mound (profile C-C, boring 35) and on the steep slopes on profile L-L at boring 77 and N-N at boring 86. The thickness of the sediment in different parts of the basin varies from 59 feet at boring 6 to none at boring 77; the average thickness is 13.96 feet.

In general, in the deep portions of the lake, the greatest thicknesses of sediment are in the depressions of the original bottom and the least on the ridges and mounds, as may be seen by comparing borings 4 (52 feet), 6 (59 feet), and 8 (36 feet) on profile A-A with those at borings 5 (27 feet) and 7 (11 feet). No sediment has been deposited on the knob (barren mound) on profile C-C. The average thickness of the sediment in the deep water region of the lake (within the 50-percentile contour, approximately the 65-foot contour of the present basin) is 19.22 feet (Table V).

That the sedimentary deposits on the steep slopes are much less than in deep water is shown by the fact that there is none at boring 77 (profile L-L, Fig. 2), which at that place has a slope of approximately 8°; there is also none at boring 86 on profile N-N, which has a slope of 7°. At boring 67 (profile J-J), where the slope is 6°, there are 6 feet of sediment; at boring 66, on the opposite side of the lake, there are 14 feet of sediment on a slope of 5.5°. The above figures suggest that the depth of sediment is somewhat inversely proportional to the degree of inclination of the slope, but that other factors play as important a rôle is shown by the fact that at boring 39 on profile C-C, with a slope of 4°, there are only 8 feet of sediment, and at boring 70 on profile K-K, there are 12 feet of sediment where the slope is 7°. The average thickness of sediment on the steep slopes of section A is 12.8 feet as determined by dividing the volume of sediment by the area that lies between the 40- and the 50-percentile contours. The sediment in section B between the 25- and 40-percentile contour (the steepest portion) averages 14.2 feet.

The thicknesses of sediment on the outer edges of the shelves (on the shore side of the steep "drop-offs") are greater than on the steep slopes. For example, boring 29 (profile B-B, Figs. 1 and 2) has a 28-foot deposit, and boring 61 (profile H-H) has 42 feet. The average depth of sediment between the 25- and 40-percentile contours of section A, a fairly representative zone on the outer edge of the shelf region, is 16.5 feet.

The depth of sediment in the near-shore zone (outside the 25-percentile contour) varies from zero in a few places at the shore edge (e.g., along Kalarama) to 25 feet, as at boring 30. The average depth of sediment in this zone is 7.4 feet.

A comparison of average thicknesses of sediment in the deep water, on the steep slopes (section A), on the shelf (section A), and in the shore zones (19.22, 12.8, 16.5, and 7.4 feet, respectively), together with the other data cited, shows a considerable preponderance of accumulation of sediment in the deep water and on the outer edges of the shelves.

The distribution of sediment in relation to the depth of the lake basin is indicated more satisfactorily by comparing the area of the basin inside and outside the 50-percentile line (p. 243). Table I shows, for the lake as a whole, that approximately one-half of the sediment lies above and below the base of frustrum 8, i.e., above and below a plane that cuts the lake basin into two parts horizontally at the level of the 40-foot contour lines of the original and present basins. The 50-percentile contour line, therefore, lies between the 40-foot contour lines of the original and present basins. A comparison of the figures shows that the average rate of accumulation of sediment has been 1.75 times as fast inside the 50-percentile contour as outside it.

That there has been a considerable variation in the manner of accumulation in the different parts of the basin is shown by the following ratios of the average rate inside the 50-percentile contour to that outside for each of the three sections: section A, 1.65; section B, 1.92; section C, 3.0 (Tables II-V). It is obvious that, in all parts of the lake, the rate of accumulation has been much faster within the 50-percentile contour than without. A comparison of the average depths of sediment that have accumulated in the regions inside the 50-percentile contours of the three sections (Table V) shows that the bottom in the deep water zone of section C has received more than its proportional share of the deep water accretions, and section A less. A similar study of the areas of the three sections outside the 50-percentile contours shows that the bottom outside the 50-percentile zone of section C has received less and section A more than their proportional shares of near-shore sediment. That the greater relative accumulation of sediment in the near-shore zone of section A, as compared with C, is responsible for this is emphasized by the fact that the average depth of sediment outside the 25.09-percentile contour of section A is 15.3 feet, while in section C the average depth of sediment is only 6 feet outside the 26.23-percentile contour.

D. Quantities of Sediment in Relation to Shallow Water Area

The total area of the original lake basin outside the 20-foot contour is 47% of the total area of the lake (Table V). Over 55% of this area lies in section C. The proportion of the area of each section that lies outside the 20-foot contour is as follows: section A, 33.4%; section B, 42.6%, and section C, 62.1% (Table V). The total number of cubic feet of sediment per square foot of area outside the 20-foot contour is as follows: in the lake as a whole, 29.67; in section A, 44.6; in section B, 30.4; and in section C, 21.7. These figures are of significance if it is assumed that a large proportion of the sediment is produced in the littoral zone.

Obviously, on the basis of this assumption, section C has had a much smaller portion of the sediment accumulate there than has been formed there, and this conclusion is emphasized by the fact that, although the area outside the 20-foot contour of section C comprises 55% of the total area of the lake outside the 20-foot contour, it contains only 40.44% of the total volume of sediment, whereas section A contains only 28.5% of the corresponding area but has 42.9% of the sediment.

E. Correlation of the Volumes of Sediment with the Areas of the Sections

The areas and quantities of sediment in different parts of the lake are as follows (Table V): section A, 40% of the total area of the original lake basin and 44.8% of the total volume of sediment; section B, 17.7% of the total area and 16.5% of the sediment; section C, 41.9% and 40%, respectively. The average thicknesses of sediment in the three sections are nearly equal (Table V). These data show that the quantities of sediment in the various sections are nearly proportional to the areas.

F. Volume of Sediment and Proportion of Basin Filled

The total volume of sediment in the lake (Table V) is 31.9% of the volume of the original lake basin, but the portions of the three parts of the basin that are filled differ greatly. Since section A had, in the beginning, an average depth of water of 64.5 feet, section B, 41.9 feet, and section C, 24.4 feet, it is apparent that the average original depths of the sections (A, B and C) are nearly inversely proportional to the parts that are filled (23.10%, 30.9%, and 55%, respectively).

G. Proportion of the Basin Obliterated

The emerged area of the original basin, i.e., the area between the original and present shore lines may be designated as the portion of the original basin obliterated. For the lake as a whole this is 20.82%, for section A, 12.22%, for section B, 16.82%, and for section C, 30.78% (Table V). The latter figures are fairly proportional to the percentages of the three sections that are outside the 20-foot contour of the original basin (33.4%, 42.6%, and 62.1%, respectively).

The percentage of filling of the lake as a whole and of the various sections of the lake basin is greater in every case than the percentage of obliteration of the shore zones of the same part.

H. "Marl Islands" and "Marl Ridges"

It has been noted (p. 238) that there are four knobs on the original bottom (Figs. 2 and 3). Three of these are covered with sediment which reaches to within three to five feet of the water surface; they are the "marl islands" located at borings 9, 11, and 96. The fourth knob, which is barren, is at boring 35; its peak lies 35 feet below the surface. The "marl islands" form conspicuous landmarks in the lake due to the growth of emergent vegetation on their peaks. The original knobs on which the "marl islands" at borings 9 and 11 are built rise to within 30 feet of the present water surface and the one at boring 96 to within 22 feet. They have deposited on them 27, 28, and 18 feet of sediment, respectively.

The sediment on these "marl islands" is relatively high in carbonates, most of it testing higher than 90% (that at boring 96, over 95%) as contrasted with 65% in borings 10, 54, and 55 which lie between the three islands.

The term "marl ridges" has been coined to indicate accumulations of sediment on projecting ridges of the original bottom (borings 49, 61, 64, 94, 72, 84, 87, 97, and 99) because of their high content of carbonates. For example, the carbonate in the top sample of sediment at boring 84 is 98% (the highest) while that at boring 72 (the lowest) is 82%.

On Figure 3 it can be seen that the contour lines of the present basin, at some of the "marl ridges" curving around the point more acutely than do the contour lines of the original bottom, indicate that the ridge has been building rapidly towards the center of the lake—in fact, more rapidly in most cases than in the embayments between the ridges, as shown by the greater depth of the sediment on the ridges than that at corresponding depths in the embayments. Like the "marl islands," the ridges are covered with vegetation.

I. Stratification of the Sediment in the Deltas of the Inlets

The borings made in the deltas of the two streams entering the lake (Fig. 1), namely, the James Lake Inlet (boring 3) and Grassy Creek Inlet (boring 50), and one in the delta of the mouth of a short but deep ravine along the north shore (boring 33) show alternating layers of marl and sand. This stratification is thought to be significant.

The logs of the borings in the three places mentioned above from the water surface down are as follows:

James Lake Inlet—water, 3 ft.; marl, 22 ft.; sand, 2 ft.; marl, 4 ft.; bottom (gravel).

Grassy Creek Inlet—water, 3 ft.; marl, 2 in.; peat, 2 ft.; marl, 29 ft.; sand, 4 in.; peaty marl, 4 in.; marl, 6 in.; bottom (gravel).

Ravine Delta—water, 15 ft.; marl, 8 ft.; 3 layers of sand alternating with 3 layers of marl, 9 ft.; bottom (gravel).

Alternating layers similar to these were found in the deltas of the two inlets of Winona Lake. They have not been described in detail. They resemble the alternating layers in the Ravine Delta of Tippecanoe Lake more closely than they do the creek inlet deltas.

J. The Nature of the Original Bottom of the Lake

The original bottom of the lake was found to be composed of gravel and sand and everywhere except at boring 86, which was on a steep slope and was composed of glacial drift. The terraces of the original bottom, around the edges of the lake and the ridges between depressions, have the largest particles (6 to 800 mm. in diameter), while the depressions have considerably smaller ones, the smallest, occurring in the deep depression at the west end of the lake, varying from 1 to 3 mm. The east half of the lake has, in general, larger particles than the west half.

6. Comparison of Tippecanoe and Winona Lakes.

Tippecanoe Lake is 11.5% larger in area and 42.6% in volume than Winona Lake. Its greater excess in volume as compared with area is due to its greater average original depth (43.7 ft. as compared with 34.2 ft.). The greatest absolute depth of the original basin of Winona Lake was 128 feet, anc of Tippecanoe, 164 feet (boring 23); the greatest present depths are 80 and 123 feet, respectively.

The area outside the 20-foot contour of the original basins is a fair measure of what has formed the littoral regions of the lakes during their past histories. Winona Lake has had 45.9% of its area outside the 20-foot contour, while Tippecanoe has had 47.0% outside (Table V).

Winona Lake has 37.4% of the original basin around the edges raised above the present water level, whereas Tippecanoe has only 20.8% obliterated. These figures are significant since, as shown in the preceding paragraph, the percentages of original littoral zones in the two basins are very nearly the same.

The absolute volume of sediment in Tippecanoe Lake is slightly more than that in Winona (Table V). These quantities, however, are fairly proportional to the areas of the original basins of the two lakes as shown by the nearly equal average depths of sediment in the two basins.

The proportion of the original basin of Winona Lake filled with sediment is 43.66% (Table V) as contrasted with 31.90% for Tippecanoe Lake. The inverse correlation existing between the proportions of the two basins that are filled and their respective average original depths (34.20 and 43.77 feet) is the same as for sections of Tippecanoe Lake (p. 243).

The percentage of areas of Winona Lake and Tippecanoe Lake that are outside the 50-percentile contours are 64.42% and 63.68%, respectively. The average thicknesses of sediment of the two lakes in these regions are 11.58 and 10.96 feet, respectively, a slight advantage in favor of Winona Lake. The percentages of areas of the two lakes that are inside the 50-percentile contours are 35.58 and 36.32, respectively, and the average depths of sediment are 20.98 and 19.22 feet; this is also a slight advantage in favor of Winona.

The ratio of the sediment that has accumulated inside to that which has accumulated outside the 50-percentile contour for Winona Lake is 1.81 and for Tippecanoe 1.75 (Table V). This is a slight advantage in favor of Winona Lake.

The 50-percentile contour occurs between the 33-foot contours of the present and original basins in Winona Lake and between the 40-foot contours in Tippecanoe. The number of cubic feet of the total sediment in the lakes per square foot of area outside the 20-foot contour are, respectively, 32.50 and 29.67, showing a considerable advantage in favor of Winona Lake and constituting a fact of some significance if a very large proportion of the sediment of the lakes has originated in the littoral zones.

7. Discussion and Conclusions

The fact that the lake basin is at present and, for some time past, has been almost completely sealed from the underlying original bottom precludes the possibility that much interchange of lake water can take or has taken place with ground water. This would imply that most of the chemicals in solution in the lake (particularly calcium carbonate) that are precipitated out to form sediment are derived, at the present time, from the surrounding terrain by surface drainage. The abrasion of the gravel, sand, and clay washed into the littoral zone of the lake is probably the source of most of the silicates and aluminates found in large quantities in the sediment, especially in the deep water zone.

The varying thicknesses of sediment found in different parts of the basin are indicative of dynamic factors at work in its distribution. That the deep-water zones have been the best depositories of sediment is, no doubt, due to the fact that when sediment settled there it remained. The outer edges of the shelves have more sediment on them than occurs on the steep slopes or in the near-shore region because they are deep enough to be below the zone of wave erosion and flat enough to retain sediment once it has fallen on them. The near-shore zone has very little sediment because much that settles there is eroded away. If that does not happen, the zone is soon filled and emerges from the water and, of course, cannot be a further depository of sediment.

That the depressions in the deep-water zone of the lake accumulated sediment much faster than did the contiguous ridges is probably due to the slower currents there when there was general circulation of the lake water. This process probably continued until the depressions were filled to the level of the ridges. After the lake bottom became more regular and smooth, deposition of the sediment was undoubtedly fairly uniform over the bottom in the deep water because the current was more regular. The fact that there is no sediment at all on the "barren mound," even now, and that the sediment around its base has, as yet, not nearly reached its level (40 feet below) is further evidence tending to substantiate this statement.

The following facts and probabilities must be considered in any theory attempting to explain the dynamic factors involved in the distribution of sediment in Tippecanoe Lake.

1. The volume of sediment in each section bears the same relation to the total volume of sediment in the lake as the area of each section bears to the total area.

2. The zone inside the 50-percentile contour in section C has accumulated more sediment, and the zone outside the 50-percentile contour less, than expected on the basis of equal rate of accumulation per square foot of area, but just the reverse relationship obtains within section A.

3. It is likely that sediment is formed equally in all parts of the deep-water zones of the lake.

4. Probably most of the sediment is produced in the shallow-water region of the lake.

5. More than 55% of the area outside the 20-foot contour of the original basin lies in section C, but section C contains only about 40% of the sediment, while section A has only 28.5% of its area outside the 20-foot contour and contains 42.9% of the sediment.

If the above assumptions are valid, then the facts cited can be explained by assuming that most of the sediment in the lake has been produced in the zone outside the 20-foot contour of section C, but that a large part of it has been dislodged and abraded by the vigorous wave action at that end of the lake, and, subsequently evenly distributed over the whole lake by currents, has settled out fairly uniformly, especially in the deep-water region. Conversely, section A at the windward end of the lake has had relatively little of its sediment in the shallow-water zone dislodged.

This theory accounts for the fact that the sediment is distributed in proportion to the areas of the three sections, i.e., is generally distributed. At the same time it accounts for the higher ratio of sediment in the zone outside the 50-percentile contour in section A and the lower ratio than expected in the corresponding zone of section C. To account for the unexpected excess of sediment within the 50-percentile contour of section C, it is only necessary to assume that not quite all the dislodged sediment from the littoral zone of section C is distributed evenly, but that slightly more of it settles out in the deep water of that section since the deep-water zone of section C is closer to the source of most of the sediment, namely, the broad littoral region of section C, than is the deep-water zone of either of the other sections. The very high ratio of shallow- to deep-water regions in section C (2.5) as compared to the same ratio in section A (.9) lends credence to this assumption.

An alternative explanation to account for the fact that section A, outside the 50-percentile contour, has received more sediment than section C is that this zone in section A has more of its area outside the 50-percentile region in deep water than is the case in section C, and, therefore, it has more area in this zone that is a good depository for sediment than is the case in section C, which is broad and flat, and, therefore, has more of its area subjected to wave attack. That this discrepancy can be accounted for by possible accretions from the two inlets is rendered unlikely by the fact that chemical analyses of the sediments in the different sections show the sediment in the deep-water zone of section C to be higher in carbonates (80-90%) than the corresponding sediment in section A (50-60%). If the sediment in section C had been deposited by the entering streams, it would have been largely silica and organic matter. Furthermore, if stream deposition were the cause of the excess, the total quantity of sediment in section C should be more than expected on the basis of equal distribution by sections. This is the antithesis of the case; it is deep-water zone of section A that has more material than expected, and section C less (page 243).

It is likely, on the basis of this theory, that it is a mere coincidence that the amounts of sediment in the three sections are nearly equal per square foot of surface, because, if the lake were turned end for end so that the large littoral zone of section C were at the west or windward end instead of the east or lee end, it is likely that section A would not have received so much sediment dislodged from the littoral zone of section C because, in that case, not so much sediment would have been dislodged from section C. It would be expected that by the present time section C would be entirely filled and section A would have only a fraction of the sediment in the deep-water zone that it does have under the existing conditions.

Since the percentages (23.1%, 30.9%, and 55%) of the three parts of the original basin (A, B, and C, respectively) that are filled are inversely proportional to the average original depths of the basin (64.5, 41.9, 24.4 feet, respectively), and since the average thicknesses of sediment in the three parts (14.91, 12.98, and 13.47 ft. respectively) are nearly equal (showing an average equal sedimentation per square foot of the area), the conclusion is inevitable that the proportions of the basins of the various sections of this lake that are filled are dependent on the original depths of the basins; the greater the original depth, the lower proportion of the basin that is filled.

The fact that the rate of obliteration of the basins (emergence of the shallow near shore zone) is fairly proportional to the percentage of the area of the various sections of the basins that lay outside the 20-foot contour can be explained on the basis that the waves break and expend their energy farther out in the lake in a broad near-shore zone than in a narrow one, and, therefore, the accumulations of sediment along the edge of the shore in the former case are less likely to be dislodged.

With the persistence of the filling of the middle of the various basins more rapidly than the areas along shore are being obliterated and the filling on the outer edges of shelves (outside the "drop off") faster than on steep slopes, it can be predicted that a condition will be reached eventually where the lake basin will have the form of a broad flat emerged zone with a steep drop-off to a body of shallow water of uniform depth in the former deepest part of the basin. From this point on it can be predicted that the rate of filling in the center will be less rapid than the obliteration of the area around the edges, because, as the lake becomes older, the rate of filling in the center will decelerate, due to less effective abrasion and circulation. This would be expected since, as the lake grows smaller, the waves become smaller. Also, with less wave action, accumulation at the edges would be expected to accelerate. The final shallow remnant of the lake would be expected to be obliterated by the typical encroaching, mat-forming association of plants characteristic of bogs.

The presence of alternating layers of sand and marl in the lower reaches of sediment in every inlet studied in the two lakes certainly indicates some general change in conditions. The most obvious suggestion is a change in climate involving considerable fluctuations in rainfall. During wet periods, with the attendant influx of swift-flowing water, it can be supposed that more sand was carried by the streams and carried farther into the lake than in dry periods. The resultant deposition of sand overwhelmed the slow deposition of the more characteristic lake sediment. During relatively dry climatic conditions the streams would be sluggish, and the amount of sand carried would be small, and it would not be carried so far into the lake; therefore, the more characteristic lake sediments would be dominant in the delta regions. The data are too fragmentary to permit any attempt to correlate the strata with definite post glacial climatic periods as has been done with pollen profiles. Further and more extensive and careful work is planned in the near future on this aspect of the sedimentation problem.

Since all the "marl islands" are built on knobs which rise to within 30 feet of the water surface, whereas the "barren knob" rises only to within 35 feet of the surface, the explanation offered for the occurrence of the two similar "marl islands" in Winona Lake seems applicable here, namely, that the knobs on which they occur were close enough to the surface to permit the establishment of vegetation, which caused the precipitation of the carbonates when they utilized the half-bound carbon dioxide in the calcium bicarbonate in their photosynthetic activity. The carbonates settled to the bottom, and they remained there because the building island was isolated from shore and, therefore, not affected by waves of translation until near enough to the surface to cause waves to break. After this point was reached, they could not build higher because their accumulations were eroded and carried away as fast as formed. The fact that the "barren knob," with its top within 35 feet of the water surface, did not support vegetation indicates that, in an early period of the lake, 30-35 feet must have been the limit of effective light penetration for plant growth and thus the critical depth so far as "marl island" formation was concerned.

This theory is in marked contrast with one made by Blatchley and Ashley (1900, p. 50) to account for "marl islands." They said, ". . . they are probably above and surrounding the orifice of a former large subaqueous spring which bubbled up from the bottom of the lake." The writer has found in the five "marl islands" studied no evidence justifying the notion that springs existed on "marl islands," or anywhere else in the bottom of the lake, for that matter. As was pointed out (p. 248), the sediment seems to have sealed off the original bottom almost completely from the present basin.

An explanation similar to that made for the "marl islands" is adaptable to the "marl ridges." They were ridges on the original bottom extending out from shore, too deep to be affected by waves but shallow enough for the growth of vegetation. The accumulations of sediment on the ridges has made them more prominent features (both vertically and horizontally) of the present bottom than they were of the original bottom; consequently there exists the peculiar phenomenon in Tippecanoe Lake of the lake shore becoming more irregular at the present time than it was in the earlier stages. In this particular lake it can be predicted that, if this process continues, the lake will eventually be cut into separate parts by further extension of the opposite points along the line K-K (Fig. 1) and perhaps at other points as well.

The gravel particles of the original bottom in the depressions are too large (1 to 3 mm.) for characteristic lake currents to have carried them from the terraces and ridges to their present location. It would be necessary to assume that the assortment took place when very large volumes of water were flowing through the lake. It is quite possible that such was the case in the early history of the lake, the source of water being the melting ice of the receding glacier. The size of the valley of the Tippecanoe River probably supports such a thesis.

The slightly larger average depth of sediment in Winona Lake than in Tippecanoe Lake (14.92 and 13.96 feet, respectively) probably falls within the range of error in calculating areas and volumes; it appears, therefore, that the productivity of sediment in the two lakes has been remarkably near the same per square foot of area on the average. To what extent this kind of comparison in quantity of sediment could be utilized as a measure of the relative biological productivity of these two lakes will have to await chemical analyses of the sediment and the determination of the relative proportions of the sediment that have arisen from biological and physical activity.

The proportions of the areas outside the 20-foot contour of the two lakes have been so nearly alike (Winona 45.9% and Tippecanoe 47.0%) that, taken alone, they do not justify any dogmatic inferences as to the relative proportions of sediment that have originated in the littoral and the pelagic zones. Assuming, however, that the deep-water areas have, per square foot, been equally productive of sediment, the fact that Winona Lake, as compared with Tippecanoe, has a greater quantity of the total sediment per square foot of littoral area (32.5 and 29.67 feet, respectively) warrants the suggestion that the Winona Lake littoral has been the more productive of sediment.

The fact that Tippecanoe Lake has a less obliterated surface zone (20.8%) than Winona Lake (37.4%), but had about the same proportion of area outside the 20-foot contour originally (47.0% and 45.9%, respectively), can be explained satisfactorily on the assumption that Tippecanoe Lake, being larger, especially longer (2.3 miles), than Winona Lake (1.7 miles) has had waves with greater energies, which have more effectively eroded the sediment lodged in the littoral zone and transported it to the deeper water.

Since the portions of the original basins filled with sediment (43.66% in Winona and 31.9% in Tippecanoe) are inversely proportional to the average original depths of the basins (34.20 and 43.77 feet, respectively), and since a similar inverse proportion holds for each of the three sections (A, B, and C) of Tippecanoe Lake, it is certain that factors other than depth are principally responsible for the quantity of sediment produced in a lake. It has been pointed out already that the quantities of sediment are nearly proportional to the areas of the lakes; thus it is obvious that, other things being equal, which is a condition almost attained in the two lakes under consideration, the relative quantities of sediment produced in these lakes are fairly proportional to the amounts of sunlight falling on them.

Bibliography

Blatchley, W. S. and Ashley, George H., 1900. The lakes of northern Indiana and their associated marl deposits. Indiana Dept. of Geology and Natural Resources. Annual report 25:31-322.

Leverett, Frank, 1915. The Saginaw lobe. The pleistocene of Indiana and Michigan. U. S. Geol. Survey. Monograph 53:123-158.

Malott, C. A., 1922. The psysiography of Indiana. Handbook of Indiana Geology, Pt. 2. Indiana Dept. Cons. Publ. 21:59-256.

Scott, Will, 1916. Report on the lakes of the Tippecanoe basin (Indiana). Indiana Univ. Studies. **31.**

Wilson, Ira T., 1936. A study of sedimentation of Winona Lake. Proc. Indiana Acad. Sci. 45:295-304.