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I hereby recommend that the thesis prepared under my supervision by Adolph E. Sandberg

entitled A Cross Section Across the Keweenawan Lavas at Duluth, Minnesota.

be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

Approved by:

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A CROSS SECTION ACROSS THE
KEWEENAWAN LAVAS AT
DULUTH, MINNESOTA

A dissertation submitted to the

Graduate School
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY.

1937

by

Adolph E. Sandberg

B. A. University of Minnesota 1929
A. M. University of Cincinnati 1931

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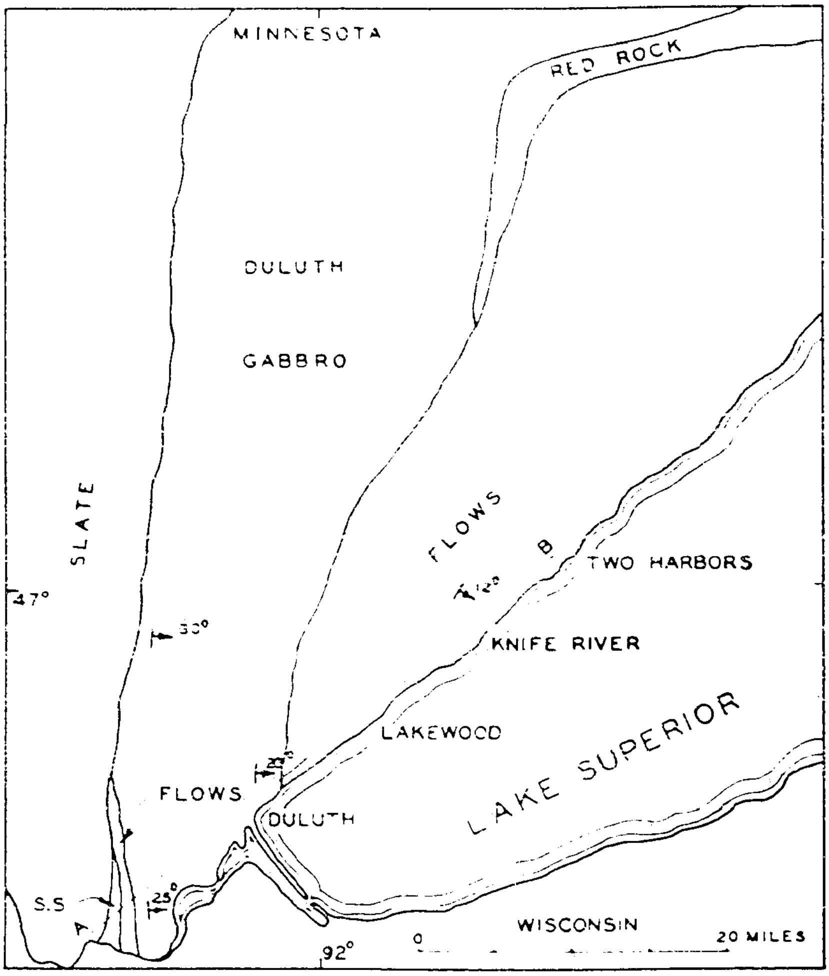
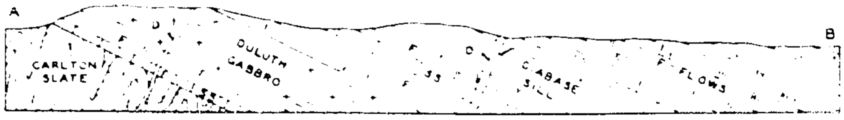
Plate 1



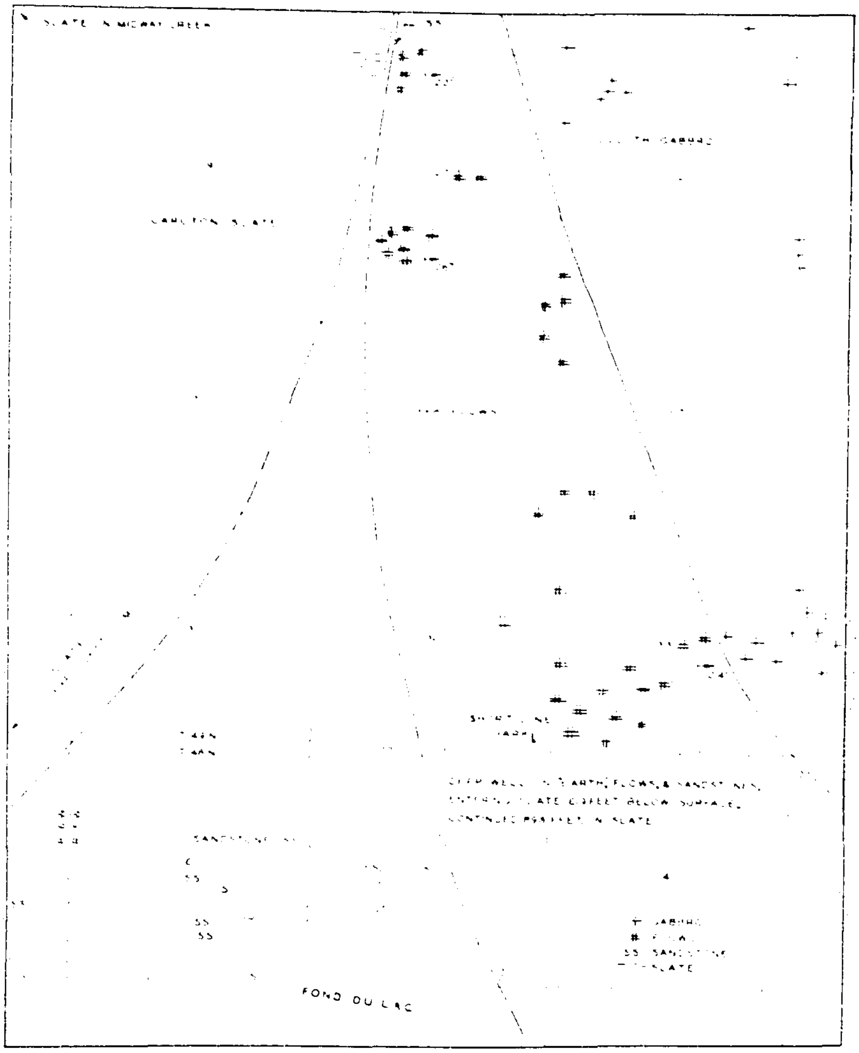
Sketch map showing areal geology. Line of traverse is essentially the line AB, following the coast line. For diagrammatic cross section along the line AB see Plate 2.

Plate 2



Diagrammatic cross section along AB, Plate 1. Not drawn to scale. General age-order is:

6. Basaltic dikes (D)
5. Probably more flows
4. Duluth gabbro and diabase sills
3. Flows and interflow sediments
2. Basal sandstone (SS)
1. Carlton slate



Map of area north of Fond du Lac, showing some of outcrops. Boundary lines, broken where not accurately known, separate areas underlain by different kinds of rock. Location with respect to Plate I is a small area on that plate in the southwest corner.

Sketch of General Geology

It would be out of place to review here the geology of the Lake Superior basin, but before proceeding further it is desireable to refer to the local geology of the area under consideration. Plate 2 represents a purely diagrammatic cross section along the line AB of Plate 1. The rocks in order of age are:

5. Basaltic dikes
4. Duluth gabbro and diabase sills
3. Lavas and inter-flow sediments
2. Basal Keweenawan sandstone
1. Carlton slate (Huronian)

During Keweenawan time this group of rocks was tilted to form the northwest limb of the Lake Superior geosyncline. The eroded edges of the successive strata are now exposed along the shore except where the latter parallels the strike.

Glacial processes have covered the rocks in places with moraines and glacial lake deposits; elsewhere considerable areas of fresh rock exposure have been laid bare. Recent wave action along the lake shore has created an almost continuous line of rock exposure by cliff-cutting, or by washing the rocks bare of their covering of lake beds. Glacially striated surfaces excellently preserved are common.

Explanation of Strip Maps

From the slate area southwest of Duluth to the lower part of the Duluth gabbro, not much detail could be worked out because of the discontinuity of exposures and ruggedness of topography. Plate 3 indicates the general geologic relations along the line of traverse below the gabbro. From near the base to near the top of the Duluth gabbro, no maps are presented as the traverse line encounters only gabbro with its various phases.

Northeastward from Minnesota Point, not far from the top of the Duluth gabbro, good detail can be worked out because of continuity of exposures, and that portion of the traverse from the top of the gabbro nearly to Two Harbors, some 25 miles away, is presented in the form of strip maps of about two and one-half miles each, labdled A-B, B-C, C-D, etc., in Plates 6, 7, and 8. These individual strips fit together into one continuous shoreline strip. The scale is 400 feet to the inch, and section lines and mileposts along the railroad are shown. Field plotting was done on a scale of 100 feet to the inch for the first few miles, the balance on a scale of 400 feet to the inch. Traverse was by pacing and Brunton compass. Locations are generally correct to within a few yards.

The contacts between flows are plotted as strike lines and projected inland a convenient distance <u>at lake level</u>. Thus, a contact line between flows a few hundred feet back from the lake on the map does not represent a contact on the land surface at that point. The actual contact could be located by projection up the dip to the bed rock surface. As a matter of fact, a few yards away from the beach the rocks are generally covered with glacial lake clays. Only rarely can an individual flow or contact be traced inland with any degree of continuity. Where the strike line on the map is broken into two dashes inland, an inferred contact is denoted.

Each rock unit, whether flow, sill, or clastic bed, is designated with a symbol, as follows:

AC = Amygdaloidal conglomerate
DB = Diabase (all are sills)
F = Felsite
M = Melaphyre
O = Ophite
R = Rhyolite
S A = Scoriaceous amygdaloid
SS = Sandstone
SS-S = Sandstone stringers

In many cases the thickness in feet is shown.

Columnar Section

The columnar section presented below was compiled by calculating the thickness of each bed along the traverse. These thicknesses were then totaled up, and the total taken to represent the thickness of the section. Figures less than 1 are ignored in the total. While it is not difficult to conjure up more favorable conditions for measuring a columnar section, the one thus obtained represents about the best that can be had. As a matter of fact, sections measured perpendicular to the strike give totals of the same order of magnitude, but have the disadvantage of extending inland where rock exposures along any one traverse line are rare.

In the tabulation of beds one column is headed Strip. This refers to the strip map on which the item referred to is found. The youngest flows are at the top of the column, the oldest at the bottom, or in other words, they are listed in stratigraphic order.

Tabulation of Beds

Strip	Rock	Thickness in feet.	Total
NE of I-J	Ophite	58	58
I-J	"	112	170
"	"	33	203
"	"	31	234
"	"	33	267
"	"	140	407
"	"	108	515
"	"	97	612
"	"	30	642
"	"	22	664
"	"	26	690
"	"	135	825
"	"	67	892
H-I	"	128	1020
"	"	53	1073
"	"	72	1145
"	"	86	1231
"	"	91	1322
"	"	38	1360
"	"	125	1485
"	"	33	1518
"	"	62	1580
"	"	35	1615
"	" (same as flow to NE)		
", G-H	Diabase sill (ophite inclusion?)	1598	3213
G-H	Ophite	207	3420
"	"	207	3627
", F-G	Series of ophites and melaphyres(under clay banks)	1444	5071
F-G	Ophite	75	5146
"	Melaphyre	61	5207
"	Ophite	46	5253
"	"	210	5463
"	SS-S	-	-
"	Ophite	49	5512
"	"	20	5532
"	"	74	5606
"	Series of melaphyres and ophites (under clay banks)	1308	6914
"	Melaphyre	15	6929
"	"	118	7047
E-F	Ophite	181	7228
"	"	237	7465
"	Sandstone	3	7468
"	Ophite	195	7663
"	"	106	7769
"	Sandstone stringer	-	-
"	Ophite	20	7789
"	Sandstone stringer	-	-

Strip	Rock	Thickness	Total
E-F	Ophite	222	8011
"	Sandstone stringer	-	-
"	Ophite	15	8026
"	Sandstone stringer	-	-
"	Ophite	33	8059
"	Sandstone stringer	-	-
"	Ophite	91	8150
"	Melaphyre	79	8229
"	Sandstone stringer	-	-
"	Ophite	148	8377
"	Sandstone	4	8381
"	Melaphyre	41	8422
"	Sandstone stringer	-	-
"	Melaphyre	52	8474
"	"	21	8495
"	"	10	8505
"	"	94	8599
"	"	107	8706
"	Ophites	354	9060
"	Melaphyre	39	9099
", D-E	Ophite	167	9266
D-E	Melaphyre	50	9316
"	"	88	9404
"	"	81	9485
"	"	50	9535
"	"	15	9550
"	"	8	9558
"	"	12	9570
"	"	22	9592
"	"	9	9601
"	"	22	9623
"	"	9	9632
"	"	14	9646
"	"	46	9692
"	"	16	9708
"	"	18	9726
"	"	30	9756
"	"	42	9798
"	Sandstone stringer	-	-
"	Melaphyre	13	9811
"	"	73	9884
"	"	48	9932
"	"	68	10,000
"	"	28	10,028
"	"	38	10,066
"	Sandstone	3	10,069
"	Melaphyre	42	10,111
"	Sandstone stringer	-	-
"	Melaphyre	33	10,144
"	Sandstone	1	10,145
"	Melaphyre	36	10,181

Strip	Rock	Thickness	Total
D-E	Sandstone	2	10,183
"	Melaphyre	16	10,199
"	"	26	10,225
"	Sandstone	1	10,236
"	Ophite	20	10,246
"	Sandstone stringer	-	-
"	Melaphyre	18	10,264
"	Sandstone	(.6)	-
"	Melaphyre	22	10,286
"	Ophite	82	10,368
"	Melaphyre	45	10,413
"	"	8	10,421
"	Sandstone	2	10,423
"	Porphyrite	31	10,454
"	Amygdaloidal conglomerate	20	10,474
"	Porphyrite	109	10,583
"	Melaphyre	21	10,604
"	Porphyrite	14	10,618
"	"	55	10,673
"	"	38	10,711
"	Melaphyre	47	10,758
"	"	98	10,856
"	"	62	10,918
"	Amygdaloidal conglomerate	23	10,941
"			
"	Ophite	56	10,997
"	Melaphyre	2	10,999
"	Sandstone	2	11,001
"	Melaphyre	6	11,007
"	"	64	11,071
"	"	92	11,163
"	"	127	11,290
"	"	64	11,354
"	"	51	11,405
"	"	31	11,436
"	"	27	11,463
"	"	133	11,596
"	"	42	11,638
"	"	16	11,654
"	"	30	11,684
"	"	37	11,721
"	"	14	11,735
"	"	12	11,747
"	Sandstone	12	11,759
"	Melaphyre	81	11,840
"	"	59	11,899
"	"	11	11,910
"	Felsite	122	12,032
"	Melaphyre	57	12,089

Strip	Rock	Thickness	Total
D-E	Sandstone	(.2)	-
"	Melaphyre	68	12,157
C-D, D-E	"	36	12,193
C-D	"	47	12,240
"	"	9	12,249
"	"	10	12,259
"	"	30	12,289
"	Sandstone	(.6)	-
"	Rhyolite	432	12,721
"	Diabase	785	13,506
"	Melaphyre	26	13,532
"	"	119	13,651
"	"	99	13,750
"	Sandstone	2	13,752
"	Amygdaloidal conglomerate	4	13,756
"	Melaphyre	25	13,781
"	"	107	13,888
"	"	90	13,978
"	Diabase	192	14,170
"	Melaphyre	114	14,284
"	"	31	14,315
"	Sandstone	1	14,316
"	Rhyolite	622	14,938
B-C	Porphyrite	68	15,006
"	Diabase	132	15,138
"	Felsite	76	15,214
"	Melaphyre	168	15,382
"	Sandstone	1	15,383
"	Melaphyre	115	15,498
"	Rhyolite	189	15,687
"	Felsite	125	15,812
"	Porphyrite	3	15,815
"	Rhyolite	16	15,831
"	Felsite	315	16,146
"	Melaphyre	4	16,150
"	Scoriaceous amygdaloid	10	16,160
"	Porphyrite	33	16,193
"	Sandstone	5	16,198
"	Porphyrite	29	16,227
"	"	73	16,300
"	"	31	16,331
"	"	111	16,442
"	"	45	16,487
"	"	85	16,572
"	Rhyolite	161	16,733
"	"	109	16,842
"	Rhyolite -part of Rh. under Diabase	14	16,856
"	Diabase	31	16,887
"	Rhyolite	445	17,332
B-C, A-B	Diabase	1295	18,627
A-B	Porphyrite	101	18,728

Strip	Rock	Thickness	Total
A-B	Felsite	14	18,743
"	Melaphyre	12	18,754
"	Diabase	64	18,818
"	Melaphyre	151	18,969
"	Amygdaloidal congl.	12	18,981
"	Melaphyre	29	19,010
"	"	16	19,026
"	Porphyrite	45	19,071
"	Melaphyre	56	19,127
"	Sandstone- some cut out by fault	114	19,241
"	Porphyrite	90	19,331
"	Melaphyre	18	19,349
"	Sandstone	16	19,365
"	Melaphyre	52	19,417
"	"	21	19,438
"	Porphyrite	98	19,536
"	Melaphyre, thin, dense	(,5)	-
"	"	45	19,581
"	Sandstone	9	19,590
"	Melaphyre	14	19,604
"	"	34	19,638
"	Sandstone	20	19,658
"	Melaphyre	32	19,690
"	"	55	19,745
"	"	27	19,772
"	Porphyrite	32	19,804
"	Melaphyre	68	19,872
"	Porphyrite	84	19,956
"	"	83	20,039
"	Porphyrites and melaphyres, at least 10 flows	1368	21,407
	Duluth gabbro	14500	35,907
	Melaphyres and porphyrites below gabbro.	2500	38,407
	Basal sandstone	50	38,457

For summary, see page 10.

Summary of Thickness by Rock Types

Rocks	Thickness in feet	Total
Basic extrusives		
Melaphyre	4,595	
Ophite	4,430	
Porphyrite	1,258	
Melaphyre and porphyrite, undifferentiated	3,868	
Melaphyre and ophite undifferentiated	2,752	16,903
Acid extrusives		
Rhyolite	1,988	
Felsite	652	2,640
Interflow fragmental rocks		
Sandstone (arkosic)	198	
Amygdaloidal conglomerate	59	
Scoriaceous amygdaloid	10	267
Basal sandstone	50	50
Intrusive rocks		
Duluth gabbro	14,500	
Diabase sills	4,097	18,597
Total thickness of Keweenawan measured -		38,457 feet.

Such a calculation of thickness as is presented above may be subject to certain errors*. These are:

1. Errors in field observations, including undetected changes in the dip, or the duplication of beds by faulting.
2. Reckoning of apparent rather than actual thickness, if the layers have a shingled, foreset structure.

With respect to the first point, it can be stated that the dips do change, but such changes are well shown, and dip readings can be taken at frequent intervals.*

As to the duplication of beds by faulting, a study of the flow sequence does not indicate that any important amount of duplication, if any, has taken place. A few beds were traced inland and these do not indicate any dip-faulting. In Plate 4 is shown a series of ophite exposures forming a low ridge. This flow is undoubtedly the thick ophite exposed along shore between Talmadge and French Rivers (Strip E-F, Plate 7). It was traced along the strike for 6 miles. To the northwest of it is a belt of diabase exposures forming a prominent ridge. This is the Lester River diabase, exposed along shore northeast of Lester River (Strip C-D, Plate 6). This sill was traced along the strike a distance of 15 miles. There was good topographic evidence to indicate that both the sill and the flow extended even farther along the strike, but time did not per-

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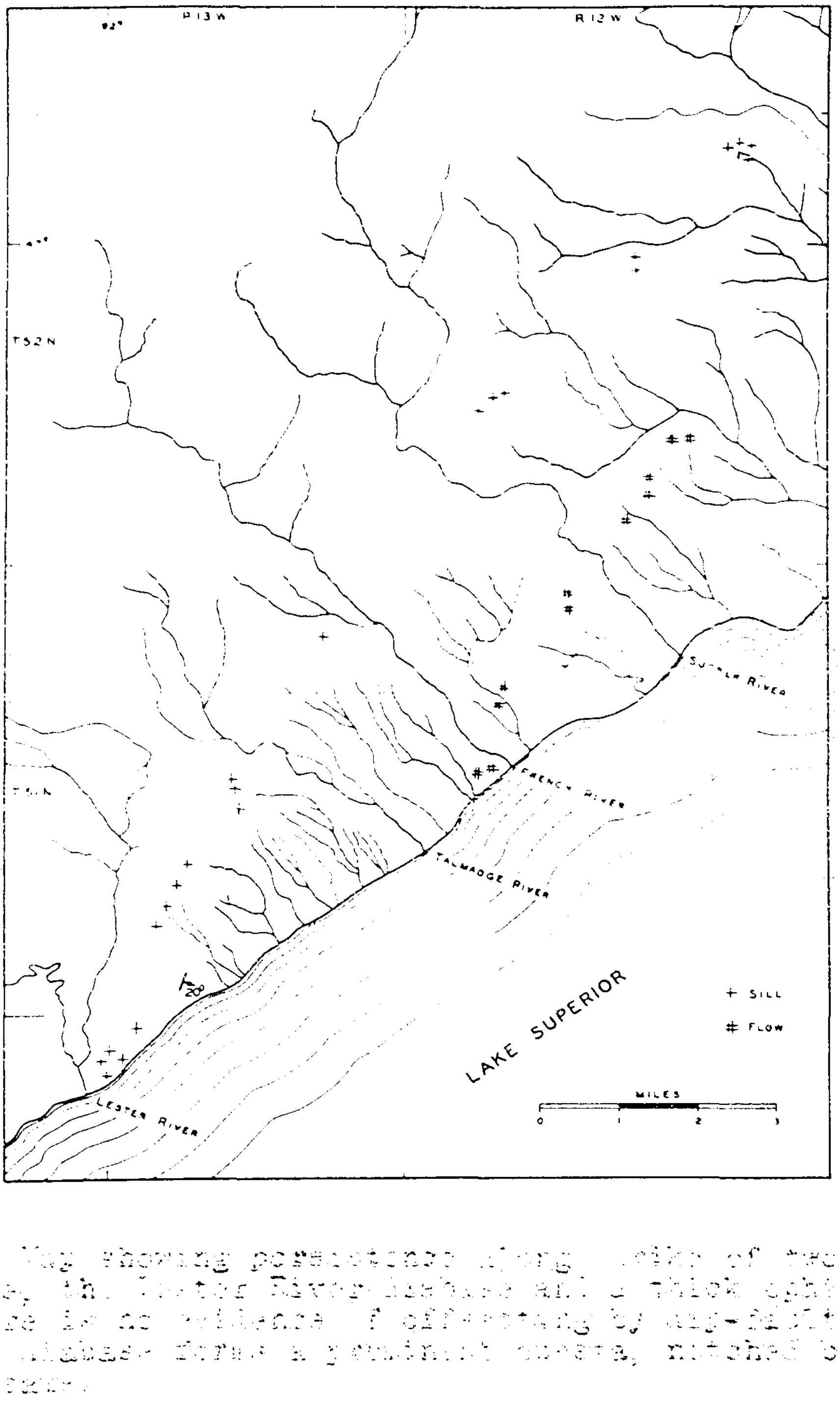
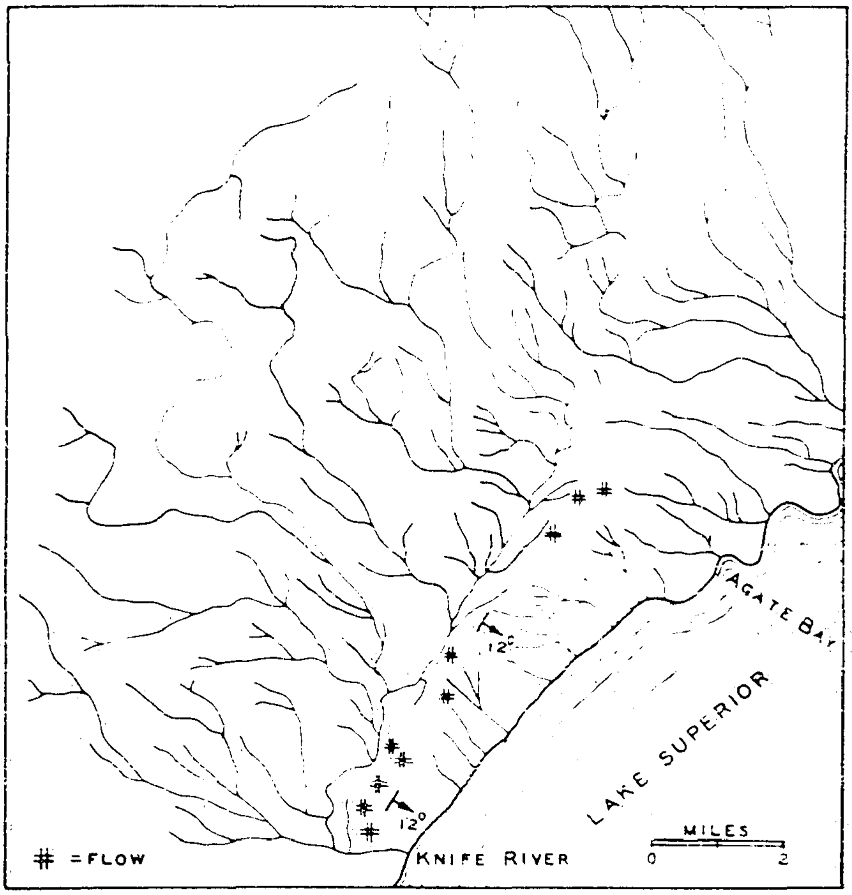
* Moore, R. C., Historical Geology, p. 94, New York, 1933

* Many more dip and strike readings are available than are shown on the maps, Plates 6, 7, and 8. Those shown represent generalizations.

Plate 4



Map showing persistence along strike of two bodies, the Lester River diabase and a thick ophite flow. There is no evidence of offsetting by dip-faults. The diabase forms a prominent cuesta, notched by streams.



Map showing persistence of flow along strike. The structure is a cuesta overlooking the valley of Knife River, with a dip slope leading down to Lake Superior.

mit tracing them out. In Plate 5 is shown a similar case of persistence of individual beds along the strike. In one case where a dip fault does occur the movement was such as to cut out beds (see p. 27).

Strike faulting, of course, may also repeat beds. Evidence for strike faults was searched for, but not found. In the few covered stretches of beach it is possible that such faults do occur, but, as already stated, there is no evidence for repetition in the flow sequence.

As to the second source of error, that is, shingling of the layers, a certain amount of this may be possible, but it presents no serious difficulty so far as the order of magnitude of the thickness determined is concerned. While this thickness may be too great for some parts, on the basis of the probable manner of accumulation of the flows (see p. 53) it is undoubtedly too thin for other sections that might be chosen.

Northeastward along the shore beyond the end of the present traverse, the lavas continue to strike at an angle to the shore line, though dips become flatter. At Two Harbors, over a mile beyond the traverse, occur at least 10 more flows.* As to how much additional thickness will be added to that already summed up when and if the section is extended to the topmost exposed beds along shore, no estimate is hazarded, though it would not be surprising if the total thickness reached 50,000 or 60,000 feet.

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* Schwartz, G. M., A guidebook to Minnesota trunk highway No. 1; Minnesota Geol. Survey Bulletin 20, pp. 70-71, 1925

Criteria Used for Distinguishing Between Successive Flows

An important part of the field work consisted in distinguishing between successive flows. While many of the flow contacts were easily recognized, some were not so obvious. The criteria used are presented below. They are offered as applying to this area, though some will apply elsewhere.

1. Most of the basalts have massive interiors, grading gradually upward into highly vesiculated (now amygdaloidal) tops. The bottom five or six inches may also be amygdaloidal, though this zone grades sharply into the dense part above.

Starting in the dense base of a flow and walking in the direction of dip, we may observe the amygdules in the dense basalt becoming more numerous until the rock is highly amygdaloidal. Here we should see the dense base of the next flow and the dipping contact between the two flows, as in Fig. 1. Proceeding farther the dense portion of the second flow gives way to amygdaloid and soon we come to the second contact, provided it is not covered. Obviously, where amygdaloidal

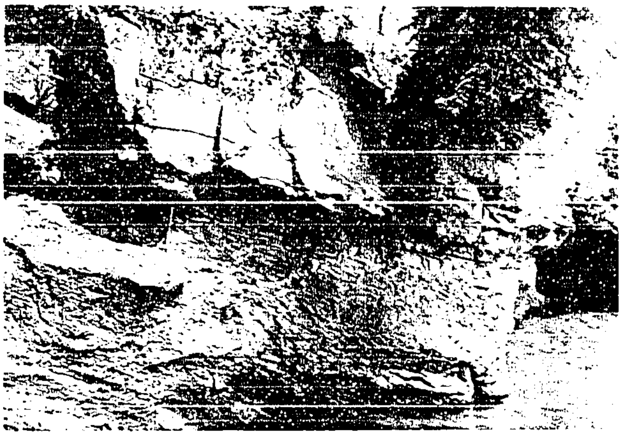

Fig. 1 Contact between flows, sharp and flat. Lower flow is amygdaloidal in upper few feet. Base of upper flow dense, with six-inch amygdaloidal zone at base.

basalt occurs on the up-dip side of a short covered stretch and dense basalt on the down-dip side, the presence of a contact under the covered area may be inferred.

Fig. 2 Contact between flows. Not so plain as that in Fig. 1, but distinguished near hammer-head. Faint suggestion of ellipsoidal structure in base of upper flow.

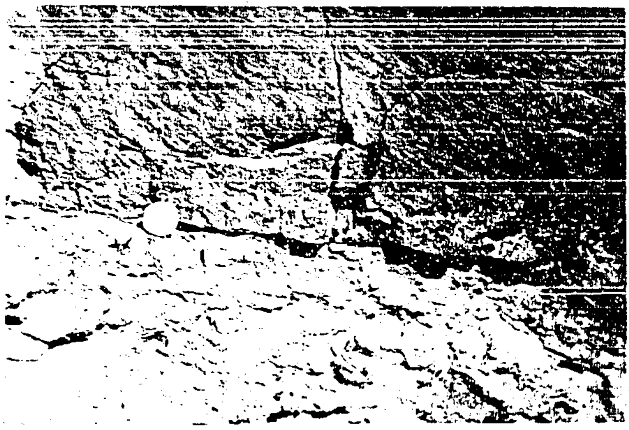

Fig. 3 Contact between flows, showing amygdaloidal top of lower flow and "pipe amygaules" in lower four inches of overlying flow. Note the watch, for scale.

3. In many of the basaltic flows the vesicles in the upper few feet appear to have flattened and coalesced, imparting a slabby or laminated character to the rock. This slabby zone is usually followed in a down-dip direction by the base of the next flow, as in Figs.4 and 5.

Fig. 4 Slabby top of one flow in lower left half of view, with dense, massive, base of overlying flow in upper right half. View sighting along contact plane.

Fig. 5 Looking down on slabby top of a flow from which the dense blocky overlying flow is being stripped.

3. Many flows have a jointing parallel to the top and base which gives them a bedded structure. Flat rock surfaces dipping in the same direction as the flows are thus produced by the stripping off of the overlying rock. When flat rock surfaces show the characteristic ropy, wrinkled, or billowy features of flow surfaces, a contact is established.

Fig. 6

Fig. 7

Wrinkled surface of basalt flows.

Fig. 8 Billowy surface of basalt flow, recently stripped of its overlying flow.

4. Columnar joints do not extend from one flow into the next. As a matter of fact, they were not seen extending clear through any individual flows, showing rather a tendency to fade out toward the tops and bottoms of flows. On the whole, the flows exhibit columnar jointing but rarely, and in no case is it well developed.

5. The tops of some of the flows show flow brecciation. Flow breccia is generally followed horizontally in a down-dip direction by the dense base of an overlying flow. No basal breccias of the type rolled under flows were seen.

6. Although many successive flows may have the same composition, texture, structure, and color, when a change in any of these occurs, a contact may be inferred, with caution. Sometimes the changes are conspicuous, as from basalt to rhyolite, melaphyre to porphyrite, or from porphyrite with phenocrysts large and abundant to porphyrite with phenocrysts small and few.

Color changes may be useful (see Fig. 9), but must be used with care as color may vary within a single flow. Changes in jointing, (Figs. 2 and 9) should be watched.

Gradation of texture from coarser to very dense strongly suggests an approach to a contact. Lane has given a discussion of a particular aspect of this in the ophites (footnote p.34).

WHile grain size, fabric, structure, color, etc., often vary within a single flow, a sharp change in any of these may indicate a contact.

Fig. 9 Contact between flows manifested by a sharp color change, as well as by a change in the character of the jointing. Dark area to lower right is lake water.

7. Inter-flow sediments form one of the most positive criteria for distinguishing between flows. These may contain basal boulders of the underlying amygdaloid, and pass upward into straight sand, or they may consist only of fine sand resting directly on the underlying flow, as in Fig. 10.

Fig. 10 Sandstone layer about five feet thick between basalt flows. Hammer-head rests on top of lower flow.

8. Soil zones between flows are a good criterion, but nothing which could be identified as a residual soil zone of Keweenawan age was seen in the section studied.

9. Clastic stringers. When the cracked surface of a flow is exposed for a time before being covered over by a later flow, sand, dust, or ash may be washed or blown into the cracks to form clastic stringers. These may or may not connect upward into a continuous inter-flow sand bed. Some sandstone stringers are soft, and tend to weather out. Others have been indurated and tend to stand out in relief by differential erosion by waves beating against the lake shore (see Fig.1). The stringers may extend down only a few inches or as much as ten feet into the flow.

Fig. 11 Clastic stringer in upper part of amygdaloidal basalt flow, Trending about parallel with the lakeward dip. The contact with the next overlying flow is found a few yards up the shore, just out of the view.

In traversing along the shore diagonally down-dip, the presence of clastic stringers presages a contact between flows, with or without an intervening sandstone layer. The actual contact may prove to be covered, but it can generally be inferred to within a few yards.

10. Topographic effects due to differences in rock resistance.

A. The type of shore line topography, that is, whether cliffs or gradual slopes front the lake, depends upon the flow. Rocks which are easily undercut, such as rhyolites, felsites, and closely jointed or crumbly basalts, make cliffs. Resistant flows, chiefly ophites and melaphyres, form low shores. Thus, a change from cliffs to gradual, low slope invites further examination of the transition zone for a contact.

B. Many of the streams entering Lake Superior have a series of waterfalls along their courses. Undercutting of

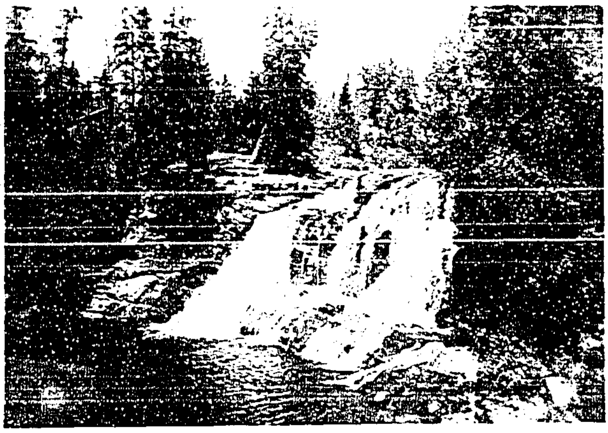

Fig. 12 Waterfalls in basalt flows. Gooseberry River.

the amygdaloidal tops forms the falls. In the simplest type the height of the falls is a close measure of the thickness of the flow. By recession the falls may leave a gorge downstream. Flow contacts are usually found near the base of the falls.

C. Caves may be hollowed out in the amygdaloidal tops of flows by storm waves beating against the shore. Their roofs are formed by the massive basal portions of flows overlying amygdaloids.

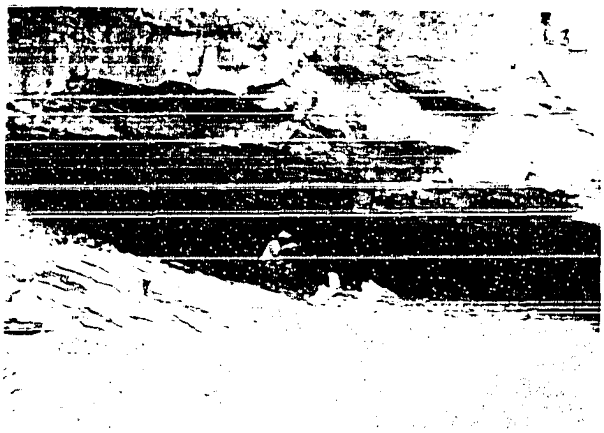

Fig. 13 Cavern in amygdaloidal top of flow with roof of dense basal portion of overlying flow. Slabby amygdaloid remnant in foreground.

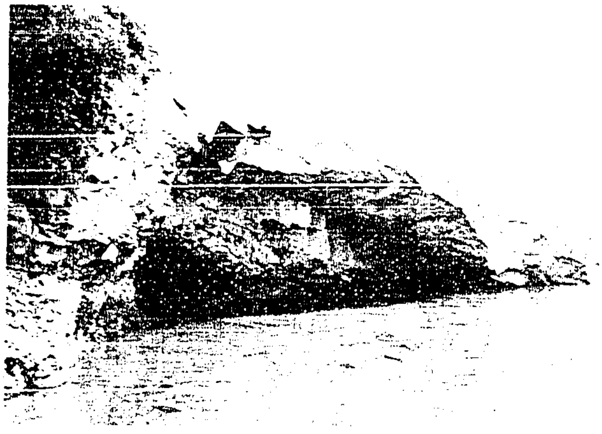

Fig. 14 Contact between flows denoted by sharp line in left foreground. Cave started in amygdaloid. Roof rock caving off.

D. Small coves or sharp indentations of the coast line are cut in the soft, amygdaloidal tops, with or without the development of caves, while the massive portions of the flows project lakeward in points. The writer found it convenient to refer to this as "cove-and-spur" topography. It is a striking feature of the coast, well known, if not understood, by local picnickers who seek shelter from northeast winds in the coves, in the lee of the spurs. In many places one may look northeastward along shore and see a succession of lakeward-dipping flows, etched out by wave action, as shown in Fig. 15

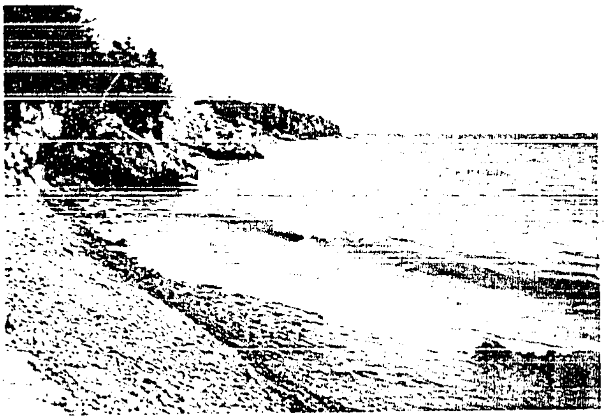

Fig. 15 Flows etched out by differential wave erosion. Tendency toward cave development also shown.

If the low cliffs shown in Fig. 15 become worn or slumped down, or are initially lower, the spurs may be lower and less conspicuous, as in Fig. 16.

The stage shown in Fig. 16 may be followed by a more advanced degree of lowering in which the shores are low and partly boulder covered, and the spurs have been reduced to low reefs, disconnected, above lake level, from the shore.

Fig. 16 "Cove-and-spur" topography, more subdued than in Fig. 15. Left foreground is amygdaloidal top of lower flow. Spur is dense base of upper flow. Contact is at base of spur.

Where a series of such reefs occurs at intervals along the shore, trending with the regional strike, each reef may reasonably be taken to represent a flow. Some flows between may show no reef. On calm days the water is clear enough to see submerged reefs.

E. Many of the streams entering the lake soon find easy cutting in amygdaloidal zones, and tend to develop asymmetrical valleys by cutting down the dip slope, undermining the resistant base of the overlying flow (see Fig. 17).

Tributaries generally come from the up-dip side with few if any coming from the down-dip or scarp side.

Streams flowing along the strike in amygdaloid may cut across the overlying basalt at nearly right angles, flow down-dip until the next amygdaloidal top is found, and then resume cutting along the strike in this weak zone. In such an angular stream course, each down-dip offset from a strike direction ideally represents the crossing of a flow.

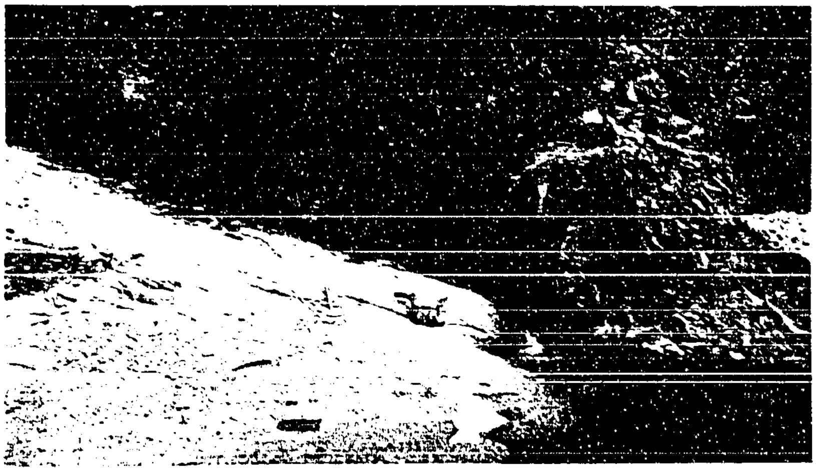

Fig. 17 Contact between flows, kept fresh by stream cutting dip slope on soft amygdaloid, against dense base of overlying flow.

F. One marked feature of the topography in districts (inland) where the Keweenawan rocks are not covered by later material is the peculiar step-like surface.* The different steps vary in size according to the thickness of the individual flows. This step-like character presents itself as follows: When one approaches from the north (the dip is south) a ridge composed of outcrops of several flows he first encounters a very steep, northward-facing slope, or even a precipitous wall, which indicates nearly, the thickness of the lowest flow. At the top of this wall is a gentler slope to the south, the slope coinciding practically with the dip of the rocks and marking the upper limit of the flow approximately but not exactly, for usually some of the loosely textured upper part of the flow has been removed by erosion. On following down this slope for

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* Grant, U.S., Copper-bearing rocks of Douglas County, Wisconsin: Wisconsin Geol. Survey Bull. 6, pp. 14-15, 1900 (quoted essentially verbatim)

a short distance another very steep slope, or precipitous wall is met, beyond which the more gentle southern slope and the steeper northward facing slope is repeated indefinitely. Where the flows are quite thick, valleys elongated in the direction of the strike, mark the separation between two flows.

Flow Units

It is quite possible, in fact probable, that some of the thin flows shown in the cross-section may not represent separate flows coming direct from a vent, but rather thin advance tongues tapped off from a larger flow. Perhaps they are "flow units".* As most of the flow contacts were seen in cross section over a range of but a few yards or more, no such detail could be worked out.

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* Nichols, Robert L., Flow units in basalt: Jour. Geol., vol. 44, pp. 617-630, 1936.

Keweenawan Rocks

The Carlton slate, which underlies the Keweenawan rocks southwest of Duluth, is given only incidental mention in this report. It is more fully discussed elsewhere.*

The Keweenawan rocks found along the line of traverse are of the same types, in general, as those of the same age found on Keweenaw Point, Michigan. The rather full descriptions of the Michigan rocks given by Butler and Burbank* fit the corresponding rocks in Minnesota so well that it does not seem necessary to repeat them fully here. Additional descriptions occur in some of the papers in the list of selected references at the end of this report.

Sedimentary Rocks

The sedimentary rocks are decidedly subordinate in the section studied. They are generally pinkish, thinly laminated sandstones showing ripple marks and cross bedding, the latter in some beds resembling that seen in dune sands. The texture is generally fine-grained, and commonly there is no basal conglomerate, the texture tending (megascopically) to be rather uniform from top to bottom. Some beds, however, do contain basal pebbles or boulders of the underlying amygdaloid. The beds are generally only one or two feet thick, one bed standing

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* Harder, E. C., and Johnston, A.W., Minnesota Geol. Survey Bull. 15, 1918.

Winchell, N.H., Minn. Geol. and Nat. Hist. Survey, Final Report, vol. 4, pp. 1-24, 1899.

* Butler, B.S., and Burbank, W.S., The copper deposits of Michigan: U.S. Geol. Survey Prof. Paper 144, 1929.

out above all others with a thickness of at least 114 feet, an unknown amount of this sandstone having been cut out by a fault. In all about 25 interflow sediments were found.

The sandstones do not contain much quartz. Feldspathic material, clay minerals, and some iron oxides are found. Possibly some wind-blown pyroclastic material occurs, but this was not definitely established. Nothing which could be positively identified as organic remains was found.

Fig. 18 Contact of red sandstone with overlying basalt. Good Harbor Bay. Cook County, Minn.

Many of the sandstones pass downward into arkosic stringers in the underlying basalt. Apparently sand was blown or washed into cracks in the exposed surface of the flow before continuous layers of sand were deposited. In a number of cases the next flow was laid down before continuous sand layers were deposited. When such contacts are exposed by erosion, arkose stringers are seen cutting down into the top of the lower flow (see Fig. 11).

Two sandstone beds near the Duluth business district have abnormally steep dips in comparison with adjacent flows. This is probably due to drag along small faults.

No felsitic sediments of the type found on Keweenaw Point were seen in this area.

Basal Sandstone

The lowermost Keweenawan formation is a basal sandstone or quartzite, found in direct contact with an overlying basalt flow, (see section 20, Plate 3). The contact of the sandstone with the underlying slate, which occurs in numerous nearby exposures, is covered. An estimate of 50 feet for the thickness of the formation in this locality is probably not far from correct.

The relation of this sandstone to those near Fond du Lac (Plate 3) is not fully established. Quite probably at least some of the sandstone exposed at Fond du Lac corresponds to that exposed in section 20 (Plate 3). No time was available for this interesting problem in the present study.

Igneous Rocks

Intrusives

Gabbro

The chief intrusive rock is the Duluth gabbro. For the most part it is a coarse phanerite composed principally of labradorite, pyroxene, and titaniferous magnetite. Peridotite, anorthosite, pegmatite, and redrock phases occur locally. Diabasic and coarse ophitic textures are found. Optically continuous areas of pyroxene several inches across inclosing feldspar laths are seen. The gabbro shows a distinct banding or fluxion structure, generally parallel to the regional dip. In major structure, the Duluth Gabbro is a lopolith. For further particulars on the gabbro, the reader is referred to various papers by Grout.*

Fig. 19 Banding in the Duluth gabbro. The dip of the bands is nearly parallel to the dip of the flows nearby. Location, North of Gary, in Sec. 34, T 49N-R 15 W.

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* Grout, F.F., Pegmatites of the Duluth gabbro: Econ. Geol., vol. 13, pp. 185-197, 1918.

Internal structures of igneous rocks; their significance and origin; with special reference to the Duluth gabbro: Jour. Geol., vol. 26, pp. 439-458, 1918.

A type of igneous differentiation: Jour. Geol., vol. 26, pp. 626-658, 1918.

The lopolith; an igneous form exemplified by the Duluth gabbro: Am. Jour. Sci., vol. 46, pp. 516-522, 1918.

Probable extent of abyssal assimilation: Bull. G. S. A., vol. 41, pp. 675-694, 1930

Origin of the igneous rocks of Minnesota: Jour. Geol., vol. 41, pp. 196-218, 1933.

Exposures of the resistant gabbro are virtually continuous along the bluff facing the lake for a distance of ten miles, or from bottom to top of the lopolith.

Diabase Sills

The term diabase is used here to denote a medium grained phanerite having a diabasic or ophitic fabric. The chief minerals are plagioclase, pyroxene, and magnetite. Ilmenite and olivine may occur also.

The rock is found mainly in sills from 30 to more than 1,000 feet thick. These have chilled borders, two contacts having been observed in which the border is a black glass showing only incipient crystallization. With increasing distance from the cooling contact the sills rapidly become medium grained or even coarse. They may "bake" their host rocks for a few feet from the contact, appearing fused to them in a strong bond. They appear to have been injected in essentially a wholly fluid condition.

Some of the sills show differentiation; for instance the one between mileposts 2 and 3, strips A-B and B-C, Plate 6.

This grades from diabase to granite.* The Lester River diabase (strip C-D, Plate 6) also contains some redrock near the top. Both sills are overlain by felsitic flows and it is not impossible that some of the redrock may be due to assimilation. Both are fully exposed from bottom to top and should make an interesting chemical-petrographic study.

Another type of differentiation occurs in the Knife River diabase (strip G-H, Plate 7). A few yards from the bottom of the rock mass, at Stony Point, there occurs an oval "boulder" of anorthosite several feet long, set in a matrix of diabase. It is made up of large crystals of labradorite up to 2 inches long. While similar rounded masses of anorthosite found in the upper portions of sills have been explained as resulting from the clustering together and rising of labradorite crystals in a crystallizing basaltic magma, the occurrence in the bottom of a sill calls for a different explanation.*

Pegmatitic patches of irregular shape, from a few inches to a few yards across occur in diabase, as along shore northeast of Stony Point (strip G-H, Plate 7), and in a road cut north of Two Harbors (Section 1, T 53 N-R 11 W).

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* Grout, F.F., Duluth rocks and structure: 16th Int. Geol. Congress, Guidebook No. 27, p. 71, 1933.

* Grout, F.F., Anorthosite and granite as differentiates of a diabase sill on Pigeon Point, Minnesota: Bull. G.S.A., vol. 39, pp. 563-565, 1928.
Grout, F.F. and Schwartz, G.M., The geology of the Rove formation and associated intrusives in Northeastern Minnesota: Minnesota Geol. Survey, Bull. 24, p.52, 1933.

Crystals of plagioclase, pyroxene, and hornblende several inches long may be found in these basic pegmatites.

Columnar jointing is not usually a conspicuous feature of the sills, though rude columnar jointing does occur. One thin sill near Tischer Creek (Strip B-C, Plate 6) is exceptional in having unusually large, regular columns (Fig. 30).

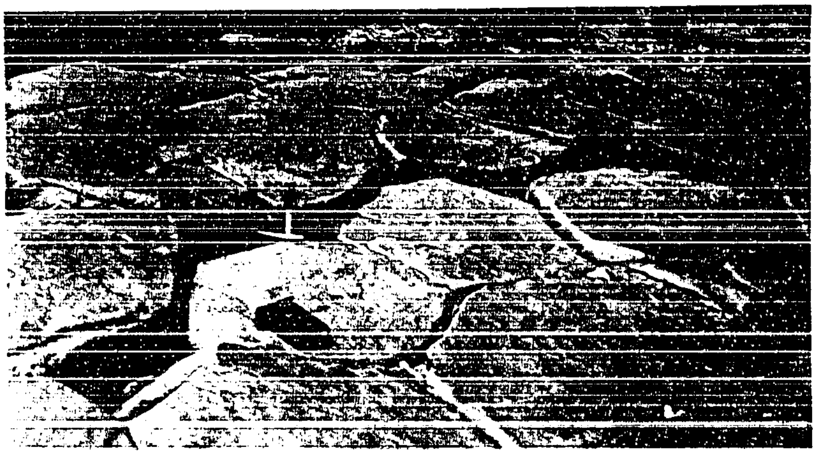

Fig. 30 Columnar jointing in thin diabase sill. Columns are 3 feet thick.

The diabases form lowish beaches, but inland they form topographic eminences, generally cuestas (see Plate 4).

Basaltic Dikes

Some 40 or 50 basaltic dikes were observed, chiefly in the lower half of the section. There is a striking similarity between all the dikes. All have dense, chilled borders with gradation of grain size toward the center. Dikes a few inches thick are aphanitic throughout; those reaching 10 feet or more may have centers of diabase. No amygdules were seen.

A rather well-developed columnar jointing is common to all, and all but the thinnest dikes have in addition a tabular jointing parallel to the walls. Most of the joint surfaces are covered with a dark green chloritic material which is generally slikensided, though generally without visible displacement. It is as though the rocks had been "kneaded" gently, with slippage taking place along the joints.

The dikes do not appear to have been fused to their host rocks. The bond is a loose one and there is a tendency for dike fragments to fall away from the host, or if the dike is more resistant the host rock may fall away, leaving the dike standing out in relief. On clear days such dikes can be traced out on the lake bottom some distance.

Thickness varies from a few inches to thirty feet. Most are from one to ten feet thick. The attitude is nearly vertical; the dominant strike is a little east of north, the dip 80°, west. The walls are usually straight and there is not much curving or branching. No primary or "flowage" brecciation was noted, nor any fluxion structure.

Near the thicker dikes in basalt pyrite, calcite, epidote and barite* seem more abundant than elsewhere.

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* The only other type of occurrence noted for barite was in cavities in rhyolite or felsite where it is associated with purple fluorite.

The dikes cut the Carlton slate and all other Keweenawan rocks, as shown diagrammatically in Plate 2, and wherever found, in whatever host rocks, there is an imposing sameness among them.

Extrusives

The extrusive rocks are chiefly basalts of various textural types, with minor quantities of felsite and rhyolite. The basalts are of the "plateau" type (see p. 43).

Thickness of Individual Flows

Flow thicknesses vary from sheets a few inches thick to flows over 200 feet. Beds from 15 to 90 feet thick are most common. Rhyolites and felsites tend to be thicker than basalts, as one would expect, and it is reasonable to suppose that they are also of lesser horizontal extent. Probably some did not flow far from their vents.

Types of Flows

The flows studied resemble those on Keweenaw Point so closely in most respects that the classification of flows adopted by Michigan geologists*is followed here.

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* Butler, B.S., and Burbank, W.S., The copper deposits of Michigan: U.S. Geol. Survey, Prof. Paper 144, 1929.

Basalts

Ophite. Ophitic texture is the roughly circular mottling of the rock produced by crystals of pyroxene that surround and enclose the feldspar crystals. The size of the pyroxene crystals varies with their distance from the contact of cooling. Thus, the so-called luster-mottling of the ophites becomes finer in texture as the contact is approached. Lane* finds that

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* Lane, A.C., Mich. Geol. Survey Pub. 6 (Geol.Ser.4) vol.1, p. 145, 1911.

of the pyroxene increases 1 millimeter for each 8 to 10 feet of distance from the upper or lower contact of the flow. This rule was tried out on Minnesota ophites and the results checked rather well. Most of the pyroxene crystals or circular "luster-mottlings" seen in the Minnesota ophites were under 5 millimeters, though very large ones occur in diabase and gabbro.

A peculiar type of weathering, possibly in part a mechanical disintegration occurs in some ophite flows. The rounded "luster-mottled" spots weather out of the rock and accumulate as a fine gravel composed almost exclusively of uniform-sized grains of this material. A good example is seen near the lake shore at Cross River, in Cook County.

In thickness the ophites range from 15 feet to well over 200 feet, the average of about 50 ophites being 90 feet. They occur chiefly in the upper half of the section, the upper flows being almost exclusively ophites.

Porphyrite. The porphyrites are rocks that contain well-defined crystals, usually of feldspar, of an older generation than the same mineral in the groundmass.

The porphyrites range in thickness from 3 to a little over 100 feet. They occur chiefly in the lower half of the section (above and below the gabbro).

Melaphyre. Melaphyre is a term applied to rocks that show none of the distinctive features indicated above. Many beds that show a distinctive texture near the center lose it near the margins, and many thin flows do not show a distinctive texture in any part. There are also some flows 100 feet or more in thickness that show no distinctive texture and are classed as melaphyre.

A variety of melaphyre is found along the lake shore which forms a group of numerous thin flows in Sections 25 and 36, T 51 N-R13 W, Strip D-E, Plate 6. This rock is finely granular, crumbly, reddish, and has small but prominent feldspars, although the rock is not porphyritic. It is here called a feldspathic melaphyre.

The melaphyres range in thickness from sheets a few inches through to flows over 100 feet thick. An average of about 100 melaphyres is 45 feet. They occur chiefly in the lower half of the section, persisting beyond the porphyrites and up into the zone of ophites.

Acid Flows

Felsite. The word felsite is used here as a field term for a dense, reddish to pinkish rock sometimes showing stubby phenocrysts and in some places a banding similar to that seen in rhyolites. A few thin sections examined microscopically contain quartz. The feldspars are usually much altered. The matrix is dense, and in places shows spherulitic-like structures. Purple fluorite and barite are common in cavities.

The rock is closely and irregularly jointed, and forms steep cliffs along the lake shore. In land it is seldom seen except in creek beds. Five felsites range in thickness from 14 to 315 feet, averaging 130 feet.

Rhyolite. The few rhyolites found in Duluth are of a light reddish or pinkish color. They are very dense in texture, and contain some visible orthoclase and quartz. Some flow-brecciation occurs, but the most conspicuous feature is a typical rhyolitic flow banding. This imparts to the rock a laminated structure whereby it resembles thin-bedded sandstone. (Fig. 21)

Fig. 21 Flow banding in rhyolite, giving the rock a thinly laminated structure. Lake Superior Shore and 43rd Ave. E., Duluth Minn.

These laminations may undulate, giving the rock a false appearance of having been thrown into gentle folds. In detail the flow lines curve around phenocrysts and inclusions.

The ropy top skin of rhyolites and felsites may be thrown into sharp isoclinal folds with an amplitude of five feet or more, by the force of oncoming lava. Such areas, initially very porous, are bleached, kaolinized, and mineralized with chalcopyrite, barite, calcite, and purple and blue-green fluorite.

Like the felsites, the rhyolites form cliffs along shore and are seldom seen inland, except in creeks.

In thickness they range from 100 to over 600 feet. The average is about 300 feet. It is not always easy to distinguish between successive rhyolite flows, and it is possible that in spite of careful search contacts may have been missed. In that case, the average of 300 feet would be too high.

Dolerite and Glomeroporphyrite. No flows of these types were recognized in the section studied.

Amygdaloids

Practically all the basalt flows are characterized by pronounced vesiculation in the upper few feet. A bottom layer, usually under 6 inches thick, may also contain vesicles (see Figs. 1 and 3). The balance of the flow generally has few if any vesicles. Thin flows may be vesicular throughout, though some are massive. The latter have been explained* as being due to thin lava sheets having poured out over a surface not yet cooled so that solidification was slow enough to permit the gas to escape before the lava became sufficiently viscous to retain it as bubbles.

Most of the vesicles in the basalts, particularly below the gabbro, are wholly or partly occupied by amygdular fillings. Common minerals recognized in the field are calcite, laumontite, quartz (agate), epidote, and chlorite, with some magnetite, pyrite, barite, and fluorite. The first five are of widespread distribution. Prehnite, almost invariably associated with small grains of copper, is abundant in localized areas.

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* Butler, B.S., and Burbank, W.S., U.S. Geol. Survey Prof. Paper 144, p.27, 1929.

Between Talmadge River and Smith Creek (Strip E-F, Plate 7), and along shore near milepost 20 (Strip H-I, Plate 8) prehnite and copper are found in place. The prehnite is not merely an amygdular filling, but appears to have replaced the rock in larers several inches thick. There is apparently nothing inherent in the rock or the structure to account for the deposition of prehnite and copper here, as in preference to other flows of similar composition and structure.

Local concentrations of resistant prehnite boulders along the beach suggest the presence nearby of bedrock supplying them, allowance being made for the strewing out along shore of boulders tossed by storm waves. Some prospecting for copper has been carried on near French and Knife Rivers, but without success.

Some of the common amygdular fillings are seen in successive layers, concentric fashion, and megascopic examination indicates the following order or paragenesis:

1. Agate
2. Chlorite
3. Epidote
4. Calcite and laumontite.

There is some overlapping of all, apparently.

The amygdular minerals are regarded as having been deposited by thermal waters percolating through the flows. These solutions were probably in part emanations from the flows, and in the main meteoric waters, heated by the flows. The meteoric waters could occur in several ways. Porous flows may contain ground water which might be heated by a later flow. In the Craters of the Moon National Monument, Idaho, water may be found dripping into lava tunnels from roofs less than 20 feet thick many weeks after a rainfall. Some hot water might be derived from rain falling on newly extravasated flows. The occasional interflow sedimentary beds suggest the probability that flows poured out on shallow bodies of water. Such a source of hot water is probably too local to account for the rather general distribution of amygdular minerals.

Lavas are known to preserve heat for several years. Mercalli* states that in July, 1914, he and Doctor Day could scorch paper in crevices in the flow of 1910 at Etna. Thus, one would expect each flow to contain warmed water for a time. The minerals may have been contributed by emanations from the flows and by solution of the flows. The close association of barite and fluorite with acid flows suggests the former.

Lindgren* writes, "That zeolitization is far from being simply an effect of the leaching by surface waters is shown by the absence of zeolites from large areas of basic flows, many of them full of vacuoles or blow-holes." As a matter of fact, solution of amygdular fillings appears to be going on at the present time in the Duluth flows. In many places cellular flows have no amygdules near the surface, but if the top material is broken away fresher rock containing amygdules can be found below.

Possibly basic intrusives are responsible for the localized occurrences of prehnite and copper.

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* Mercalli (Vulcani attivi della terra, p. 189, 1907) cited from U. S. Geol. Survey Prof. Paper 144, p. 33, 1929.

* Lindgren, W., Mineral Deposits, 4th ed., p. 516, 1933

In general, the vesicles do not show extreme elongation such as results from continued flowage up to the moment of "freezing". Most of the flows appear to have congealed from a standing liquid, yielding spheroidal or potato-shaped amygdules. However, there are flows at irregular intervals in which the vesicles are drawn out in the direction of flowage to lengths equal to five or ten times their width. Where exposures show this extreme drawing out of vesicles, the trend of elongation is markedly parallel, and is used to determine the line along which the lava flowed.

Another type of vesicles gives the actual direction of flowage at the time the lava "froze". These are the so-called pipe amygdules, shown in diagram by Emmons.* Bubbles rising from the base of a flow may become drawn out into pipes resembling the elongated bubbles generally seen in ice cubes frozen in refrigerator ice trays. If the viscosity decreases gradually upward and if the flow is urged forward, the tops of the pipes may be bent over in the direction of movement. Secondary minerals may fill the pipes to form amygdules. Pipe amygdules are not overly common in the Duluth flows, and most of those seen were of the straight type seen in Fig. 3.

The amygdaloidal and other features of flow tops are of considerable importance in the Michigan flows, as indicated by the following quotation,* "The copper derived from the

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* Emmons, Thiel, Stauffer, and Allison, Geology: p. 340, New York, 1933.

* Butler, B.S., and Burbank, W.S., The copper deposits of Michigan: U.S.Geol. Survey Prof. Paper 144, pp. 27-28, 1929

amygdaloidal tops of the lava flows has amounted to nearly half the total production and now exceeds that from conglomerate lodes and fissures combined. The greatest part of this production from amygdaloids has come from only six flows of the scores that are present. It is essential, therefore, that the character and method of origin of these upper parts of the flows be understood if a clear idea is to be gained of the conditions that determined the deposition in them of commercial ore." The full discussion of these features of Michigan flows by Butler and Burbank applies in most respects to the Minnesota flows, and the reader is referred to their paper for fuller details than are presented here.

Character of the Flows

The flows correspond to the type of volcanic rocks known as plateau, or fissure flows the characteristics of which have been summarized by Washington*, essentially as follows:

General

1. They have characteristically issued from fissures, although this quiet extrusion is sometimes accompanied by minor explosive activity.
2. They form flows of very great extent, indicating a high degree of fluidity at the time of extrusion.
3. The flows are individually of considerable thickness and the total thickness of the series of superimposed flows is very great.
4. Ash beds and layers of scoria are not abundant.
5. In several regions the basalts are associated with flows of rhyolite or toscanite, while accompanying andesite and trachyte are rarely met with, and lenadic lavas, such as phonolite or tephrite, seldom or never occur.
6. They have been extruded at very different geological epochs, from the pre-Cambrian to recent times.

Megascopically

1. They are very dark, black, or occasionally brownish black, rarely dark gray.
2. In granularity they may vary from rather coarsely doler-

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* Washington, H. S., Deccan traps and other plateau basalts: Geol. Soc. America Bull. 33, pp. 765-804, 1922.

itic to densely aphanitic, some few being evidently highly vitreous.

3. Vesicular forms seem to be rare as compared with ordinary basalts of volcanic cones.
4. The great majority are aphyric, but there is some tendency to a porphyritic development of the feldspar.
5. Augite seldom forms megaphenocrysts, and these small and sparse, while olivine phenocrysts are very rarely present, except in some of the Algonkian and Palisadan diabases.

<u>Microscopically</u>

1. Thin sections show a striking uniformity in mode, or at least in general mineral composition.
2. Augite and a labradorite (generally about $Ab_1\ An_2$) make up about 90 percent of the rock in most cases, and in all these two minerals form much the greater part; both are present in approximately equal amounts, although there may be some variation in the preponderance of one over the other.
3. The augite is colorless or, more generally, slightly brownish, and seems to be commonly an enstatite-augite in all the regions, that is, the hypersthene molecule is present in the pyroxene in amount about equal to that of the diopside molecule. This is in strong contrast with common basaltic augites, such as the loose crystals at Etna, Stromboli, Vesuvius, the Alban Hills, and Haleakala, which are dominantly diopsidic.
4. The augite is almost always interstitial, and consequently anhedral.

5. The plagioclase is practically always tabular, and euhedral or subhedral. The ordinary twinning lamellae are always present, zonal structure is rare or absent, and it carries almost no inclusions.
6. Orthoclase is seldom present; so that the molecule of this must exist in solid solution in the labradorite.
7. In the typical plateau basalts no nephelite is present.
8. Olivine is generally rare, except in the Algonkian and Palisadan regions; in the typical Deccan and Oregonian basalts it is but sparingly present in a few specimens.
9. Neither hornblende nor biotite seems to be present as a normal constituent in any of the regions.
10. Quartz is not usually present in the basalts, although many of them show an excess of silica in the norm. It occurs in many of the Palisadan diabases, however, in micropegmatitic patches interstitial between the pyroxene and the feldspar.
11. Magnetite is common in all the holocrystalline plateau basalts and in decidedly large amount. Its quantity diminishes, however, with increase in the content of glass.
12. The magnetite is evidently highly titaniferous, and ilmenite is present in many of the basalts, forming thin plates.
13. Apatite is common in the usual small prismoids.
14. In crystallinity the plateau basalts vary from entirely holocrystalline to quite vitreous forms. The amount of

glass may vary from none to about 25 percent, rarely more, and small local occurrences of almost holohyaline basalts may occur.

15. The glass is either colorless or so crowded with "dust" that it often appears to be opaque, or is yellow.
16. The content in augite, and still more in magnetite, decreases with increase in the amount of glass, pointing to the conclusion that these two minerals are the last to crystallize, and that the glass has the composition of a mixture of augite and magnetite.
17. The microtexture is most often ophitic, the thin tables of labradorite lying in an interstitial mass of anhedral augite grains. Less often it is intersertal, and still less often is a typical "basaltic" texture shown.
18. Textural evidence of flow is seldom seen.

Direction from which Lavas Came

An attempt was made in the field to determine the direction from which the lavas flowed. The following types of observations were used:

1. Direction of elongation of vesicles. This will give the line, but not the direction along that line. While flows may move in diverse directions locally, as in flowing around a swell or hill, the sum total of a large number of readings should be reliable.
2. Bending in pipe amygdules (see p. 41).
3. Trend or pattern of wrinkles on top surface of flow. In Figures 6 and 7 the pattern of the wrinkles is such as to indicate a direction of flowage toward the top of the view.
4. Flow lines in rhyolite. While these may show a platy character, parallel to the top and bottom of the flow, they often have a definitely linear character with a pronounced parallelism of the various linear streaks.
5. Position of flow terminals. Only one terminal was seen. It is shown in Fig. 22. The flow terminal faces up-dip and the flow came from a down-dip (easterly) direction.

If the trends determined by the criteria outlined above are plotted, some notion of the direction from which the flows came is obtained. The plotting of 70 observations indicates that the flows came from a direction or directions between south 52° E and north 63° E with a dominant direction of from 11° north of east to 16° south of east or in other words, from the direction of the present Lake Superior.

Fig. 22 Flow terminal. A thinly laminated, cross-bedded sandstone, now dipping to the right was partly covered by a dark red flow (lower right). Shortly after, a second flow covered the earlier, dark flow and the remaining sandstone surface in front of it. The hammer rests on the later flow, above the sandstone and in front of the earlier flow.

Probable Distance from Source

Close to a source of volcanic eruptions, which we may suppose for purposes of discussion were more or less evenly spaced in time, a vertical column would include all or nearly all the flows that had been extravasated. Some eruptions may have been greater than others and would have flowed farther from the source, a certain number reaching to the outer portion of the lava field. Farther from the source, a vertical column at a given point would include those flows which had flowed to the edge of the lava field or to some distance farther from the source than the given point, and would not include those flows which had flowed a shorter distance. The average time interval between flows in the column near the source would be less than that in the column farther away.

If there were interflow periods near the source sufficiently long to permit sedimentation, erosion, or soil formation to take place, surely at a more remote point, not reached by all the flows, the chances for sedimentation, erosion, or soil formation would be even greater. If 10 successive flows fell short of this remote point there would be 11 times as long an interflow period as at a point inundated by all flows.

A point near the edge of the lava field or plateau would have been attained only by the greatest of the flows, many having fallen short. Here one might expect extensive soil horizons, sediments laid down in ephemeral lakes, or evidence of erosion between flows.

The proposition is rudely analagous to the matter of interglacial soils, studied by Kay, Leighton, McClintock, and others.

Before applying this line of reasoning to the Duluth flows, let us review the evidence pertaining to inter-flow periods in the section studied.

1. Upwards of 200 successive flows occur.
2. At not a single contact could an interflow soil zone be identified.
3. No case of extensive interflow erosion was recognized.
4. The thickness ratio of interflow sediments to flows is as 1 to 75 or 100. (It is possible that some of the interflow clastic material is of pyroclastic origin. If so, the ratio given may be too high as an indicator of interflow time). The majority of the sediments are very thin.
5. Including arkose stringers in the tops of flows, there is one interflow sediment for every six or seven flows.
6. The sediments are mainly of the mineralogic composition and texture that one might expect to be derived from basalts with low relief, not quartz sands such as might be washed in

from quartzose rocks outside the lava plateau.

7. A good many of the flows appear to have achieved emplacement while still in a fluid condition, as though continued flowage was limited by topography rather than by increasing viscosity.

8. Not a few flows appear to have "frozen" while still urging forward.

Having in mind a plateau comparable in size to the Snake River Plain in Idaho, it is concluded that the flows along the section studied occupied a position neither near the outer margin of the lava plateau nor close to the fissures from which the lavas came, but rather in a more or less intermediate position.

In such a position one might reasonably expect:

1. Little or no soil formation because of the inadequacy of time between flows.

2. Minor erosion partly because of the maintenance of a condition of low relief by outpourings of highly fluid basalts.

3. A moderate quantity and number of thin inter-flow arkosic sediments of fine texture, and some amygdaloidal conglomerate.

4. An interlarding of fluid flows with a few viscous ones. The fluid flows may be thought of as extending beyond the point of observation, some perhaps reaching the edge of the lava plateau, while the viscous ones were reaching the limit of their ability to urge forward. This limit was actually reached, at the line of the section, by the flow illustrated in Fig. 22.

Dikes as Possible Feeders

There might well be a tendency to consider the possibility that the numerous basaltic dikes in the Duluth area represent feeders to flows higher up. They are not so regarded by the writer, for the following reasons:

1. The "family resemblance" between all the dikes in all respects is of the order of "identical twins". Color, structure, mineralogy, texture, gradation of grain, etc., are monotonously the same in all. This sameness does not harmonize with the observed differences in flows.

2. Phenocrysts are characteristically absent, while many flows have phenocrysts.

3. No evidence of vesiculation was noted in any dike.

4. Hot magma issuing through narrow fissures in quantities sufficient to form thick, extensive flows might reasonably be expected to bring the temperature of the wall rocks up to a point such that chilled, dense to glassy borders would not be formed.

5. Such hot magma in passing upward through rhyolite might be looked for to effect some solution of or reaction with the host rock. Nothing like this was seen in the several dikes cutting rhyolite.

6. Chilled dikes cut the Duluth gabbro and diabase sills, which suggests a late age, possibly, though not certainly, after flow-accumulation was completed.

7. No dikes passing into flows were seen. This is negative evidence, of course, but coupled with the fact that the dikes

do not show the variation seen in flows and show no vesiculation, it is worth mentioning.

8. There is no crystal orientation suggesting flow structure.

9. The principal trend of the dikes is at a fairly high angle to the axis of the structural basin in which accumulating evidence indicates the fissures occurred.

10. None of the dikes show any fracturing or brecciation such as might result from resurgence of volcanic activity along an established fissure.

The dikes appear to have been injected into "cold" rocks, probably at a depth of the order of a mile or more, into preexisting cracks, suddenly, and in a completely liquid condition, with enough force to crowd the walls apart to form dikes 30 feet thick. Each dike appears to represent a single charge of liquid magma which cooled and crystallized _in situ_. The episode of dike intrusion was probably associated with the slumping of the Lake Superior basin.

The Lake Superior Geosyncline

Hotchkiss* has advanced a hypothesis for the origin of the Lake Superior geosyncline which "relates the origin of the various formations and their present structure to the intrusion of an enormous bathylith, whose final result is evident to us in the scores of thousands of cubic miles of Keweenawan lavas and intrusives. The gradual foundering of the roof of this bathylith is believed to offer the most plausible explanation of the origin of the present structure."

On the Michigan side of the basin there is evidence to show that the flows came from a northerly direction. Tanton* finds evidence on the north shore of Lake Superior in Ontario that the flows came from the south. In the Duluth area the flows came from the east and a little south of east (see p.48). Thus there is evidence to indicate that the axis of the Lake Superior geosyncline was the axis of Keweenawan fissure eruption.

Hotchkiss refers (p. 671) to the fanning of the dips in the Keweenawan of the south shore. The flows at the south are

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* Hotchkiss, W.O., The Lake Superior geosyncline: Geol. Soc. America Bull., vol. 34, pp. 669-678, 1923.

* Tanton, T. L., Shore of Lake Superior between Port Arthur and Nipigon: Canada Geol. Survey Summary Rept. for 1919, pt.E, p. 3e, 1920.

Fort William and Port Arthur and Thunder Cape map areas, Thunder Bay district, Ontario: Canada Geol. Survey Mem. 167, p.64, 1931.

practically everywhere steeper than those on the north. In the Duluth area there is a similar fanning of dips, the lower beds having steeper dips than those stratigraphically higher.

This fanning of dips fits in with the picture of a lava plateau over which basaltic flows are poured in large quantities. An essentially level surface is maintained by continued sinking as the flows are extravasated. The earliest flows have partaken of all the sinking; the latest flows have sunk the least. The thickness of flows would be least near the edge, greatest near the center or axis of depression. Hotchkiss (p. 677) writes, "During the time of extrusion there was a slow progressive sinking of the range which nearly kept pace with the thickness of the extruded flows. This sinking was probably one of the chief causes of the continuance of extrusion- the load sank into the magma reservoir and squeezed the magma out."

Geologic History Interpreted from Cross Section

The following sequence of events is recognized (refer to Plate 2):

1. Erosion of the Carlton Slate, followed by deposition of basal quartz sandstone. This represents a great unconformity.

2. Basalt flows were extruded over this sandstone. The character of the surface on which the first basalt was laid down is not known. The first basalt, seen in direct contact with the underlying sandstone in section 20, Plate 3, shows no particular evidence of having been laid down in water. It is a massive flow much like other higher flows known not to have been deposited in water. There is some evidence of accumulation of clastic materials between some of the early flows under the gabbro but the amount is subordinate. In the column as a whole, there appear to have been frequent interflow periods of short duration; none long enough for soil horizons to form.

3. The Duluth gabbro was intruded after the accumulation of a certain number of flows. How many flows had been poured out before the gabbro was intruded is not known; probably a fairly great thickness, for the gabbro is a plutonic rock type and it does not seem likely that its emplacement could have occurred at a depth of less than some thousands of feet.

4. A series of diabase sills was intruded at some time before, during, or after the intrusion of the gabbro, just when is not known. Possibly they are more or less contemporaneous.

5. More lava flows may have accumulated after the gabbro and sill intrusions.

6. There was a progressive settling of the Lake Superior basin as the flows accumulated. Just when this settling began is not known. Possibly it began before a very great thickness of flows had accumulated and continued until the close of Keweenawan time.

7. A series of basaltic dikes was intruded after the emplacement of the gabbro and sills, and possibly after additional flows had accumulated. It has been pointed out that these dikes have chilled borders and generally dense texture, except the centers of dikes over 10 or 15 feet thick, in whatever rocks they intrude. This means that they were injected not only after emplacement of the gabbro and sills, but after these masses had become completely crystallized and cooled to a sufficient degree to effect the chilling. The dikes, therefore may be of rather late Keweenawan time.

It would be interesting to make radioactive time determinations on three different samples, one of the earliest flows, one of the gabbro or the sills, or both, and one of the dikes. There is surely a considerable lapse of time between the earliest flows and the chilled dikes cutting the gabbro.

Of the late history of the Keweenawan little can be learned in northeastern Minnesota, for the top of the section is not exposed.

Duration of Keweenawan Time

Van Hise and Leith* have expressed the opinion that "the

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* Van Hise, C.R., and Leith, C.K., The geology of the Lake Superior Region: U.S.Geol. Survey Monograph 52, p.420, 1911

Keweenawan probably required as long a time for its formation as the average geologic period, such as the Silurian, Devonian, and Carboniferous, and it may have been as long as the Cambrian."

What portion of Keweenawan time was occupied with the deposition of the rocks studied at Duluth is not known. Any conclusions presented here refer only to the section studied. It includes probably 250 flows with about 25 interflow sediments (including clastic dikes in flow tops, not passing into continuous sand layers). It is considered too speculative to assume any definite value for the average inter-flow period. Depending on various factors, basalt flow surfaces may remain fresh for a long or a short time. In Idaho there occur flows which preserve almost their original freshness after at least 400 years and possibly as much as 1000 years.* Probably after several thousand years more they will still remain somewhat fresh. The climate, of course, is arid.

If the Keweenawan period endured for 50,000,000 years, it seems likely that the deposition of the Duluth flows may have required but a fraction of this time, for the picture is one of rather rapid accumulation of flows. That portion of the period occupied with erosion and the deposition of conglomerates and sandstones of later Keweenawan may have been of long duration.

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* Stearns, H. T., Craters of the Moon National Monument, Idaho: Idaho Bur. Mines and Geol., Bulletin 13, p. 21, 1928.

Differentiation

In contemplating a thick series of flows such as occurs at Duluth it is only natural to wonder if there is any evidence of progressive or rhythmic changes in the composition of the lavas from bottom to top of the section.

From a study of the tabulation of flows presented on pages 5-10 the following groups are recognized, from bottom (1) to top (7):

7. Ophites
6. Ophites and melaphyres
5. Melaphyres (thin flows, feldspathic)
4. Melaphyres with ophites and porphyrites
3. Melaphyres
2. Acid flows with melaphyres and porphyrites
1. Melaphyres and porphyrites

Certain factors tend to obscure the relation of any observed flow sequence to processes of differentiation within the earth's crust. For instance, at a given place, only those flows are seen which extended that far from the source. These factors have been discussed by Broderick.* Regarding the flow-sequence shown above, we must add to these obscuring factors the fact that little is known at present of the details of chemical and mineralogical composition of the various flow types. Possibly when the composition of the flows is worked out in detail and when more is known about differentiation within

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* Broderick, T.M., Differentiation of lavas of the Michigan Keweenawan: Geol. Soc. America Bull., vol. 46, p. 553, 1935.

the earth's crust, the observed flow cycles may be related to processes of differentiation.

A detailed study of this type was made by Fermor*, who examined specimens of 27 successive flows penetrated by a borehole over 1200 feet deep in Deccan traps. He indicates that the difference between 5 groups of flows can be explained on the hypothesis of differentiation within a quiescent magma, and refers the 5 groups to their relative positions within the magma reservoir. He writes (p. 227), "According to the hypothesis adopted by the present writer, the basaltic lavas of fissure eruptions are derived either ultimately or directly from an infraplutonic shell of basaltic composition but eclogitic phase, release of pressure over a sector of the earth's crust permitting the passage of eclogite into liquid basalt with formation of an infra-plutonic (?subcrustal) magma reservoir."

"There appears to be no evidence whether eruption usually takes place at once from such an infra-plutonic magma-reservoir, either direct to the surface to fill an intermediate intercrustal magma-reservoir, or whether there is usually a period of quiescence in the infra-plutonic reservoir before eruption, during which stratification of the magma might by differentiation result."

Various students of the Keweenawan have referred to the occurrence of acidic lavas associated with basalts. The ratio in the Duluth section is about 1 of felsite to 7 basalt, which

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* Fermor, L.L., On the basaltic lavas penetrated by the deep boring for coal at Bhusawal, Bombay Presidency: Records, Geol. Survey of India, vol. 58, pt. 2, pp. 93-240, 1935.

resembles the ratio of red rock to gabbro in the intrusives at Pigeon Point and elsewhere.*

During periods of quiescence the rhyolites are supposed to have differentiated from the basaltic magma. When extrusion began afresh, the character of the flows would differ, more or less, from the preceding flows to correspond with the degree of differentiation that had taken place.*

If we regard the flows, the Duluth gabbro and sills, and the later dikes as having a common origin, or coming from the same reservoir, the presistence of basaltic activity is impressive. While the only cases of differentiation that can be identified as such in the field took place <u>in situ</u>, in independent chambers, such as the Duluth lopolith, and in sills, the correspondence between ratios of felsite to basalt in flows and red rock to gabbro (or diabase) in intrusives may be significant.

The question as to <u>how</u> differentiation takes place arises. Fenner* has recently referred the curious phenomenon of repeated alternate outpourings of basalt and rhyolite with little or no intermediate magma, and the difficulty of reconciling it with crystal fractionation. He points out that the two magmas

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* Grout, F.F., personal communication

* Hotchkiss, W. O., The Lake Superior geosyncline: Geol. Soc. America, Bull., vol. 34, p.677, 1923.

* Fenner, C.N., A view of magmatic differentiation: Jour. Geol., vol. 45, pp. 161-162, 1937.

are evidently closely related in some manner and are affected by the same eruptive forces, their successive outpourings following each other during a short igneous cycle, and sometimes are almost simultaneous, as though requiring the coexistence of basaltic and rhyolitic liquids. He poses the questions: Has the rhyolite been derived from the basalt? How has this been accomplished without the production of intermediate magmas? What is the relative position of the two magmas in the crust, and by what disposition of outlets does each reach the surface without communication with the other?

There does not seem to be any definite answer to these questions as yet. The alternation of rhyolite and basalt in the Duluth flows is set on record here as an additional example of a phenomenon which has engaged the attention of petrologists.

A careful study of Michigan flows by Broderick* shows a certain flow sequence, but this does not, according to him, fit into a consistent picture with any process of differentiation within the magma chamber.

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* Broderick, T.M., Differentiation in lavas of the Michigan Keweenawan: Bull. Geol. Soc. America, vol. 46, pp. 503-558,1935.

Abstract

1. A cross section across the eroded edges of dipping Keweenawan strata was measured diagonal to the strike.

2. The sequence of strata was noted and the thickness measured. Detailed maps are presented.

3. A tabulation of strata in stratigraphic order is presented, together with thicknesses.

4. A summary of thickness by rock types shows: basic extrusives, 16,903 feet; acid extrusives, 2,640 feet; interflow fragmental rocks, 267 feet; basal sandstone, 50 feet; Duluth gabbro, 14,500 feet; diabase sills, 4,097 feet. The total thickness measured is 38,457 feet. This does not carry the section to the topmost exposed Keweenawan along the line of traverse.

5. Possible errors exaggerating the thickness are discussed, and it is concluded that the thickness given is of the right order of magnitude.

6. Criteria for distinguishing between successive flows are discussed.

7. The Keweenawan formations are described.

8. Amygdaloids are discussed. The amygdular fillings are regarded as deposited from thermal waters. The order of paragenesis is stated.

9. The "plateau type" character of the flows is pointed out, and Washington's statement of the characteristics of plateau basalts is presented.

10. The direction from which the lavas came is determined by various criteria, and the present axis of the Lake Superior

basin is thought to have been the site of the fissures.

11. The Duluth flows were at an "intermediate" distance from the source of eruptions.

12. The many dikes in the Duluth area are not regarded as feeders for flows higher up. They are regarded as comparatively late episodes in the Keweenawan.

13. Hotchkiss' hypothesis for the origin of the Lake Superior basin is discussed in the light of new evidence, which supports it.

14. The sequence of events from Huronian to late Keweenawan time is stated:

A. Erosion of Carlton slate and deposition of basal sandstone.

B. Extrusion of basalts.

C. Intrusion of Duluth gabbro.

D. Intrusion of diabase sills (possibly near time of gabbro).

E. Possibly more flows extruded after C and D.

F. Settling of Lake Superior basin during extrusion of flows.

G. Intrusion of basaltic dikes.

15. While the duration of Keweenawan time may have been as long as 50,000,000 years that portion occupied with the extrusion of the Duluth flows is regarded as but a fraction of this period.

16. The flow sequence by groups of flows is stated, and sub-crustal differentiation is discussed. The alternate outpourings of basalt and rhyolite are discussed, and reference is made to the persistence of basaltic igneous activity in the Duluth rocks. No conclusions as to the relation of the observed flow sequence to sub-crustal differentiation can be drawn at present.

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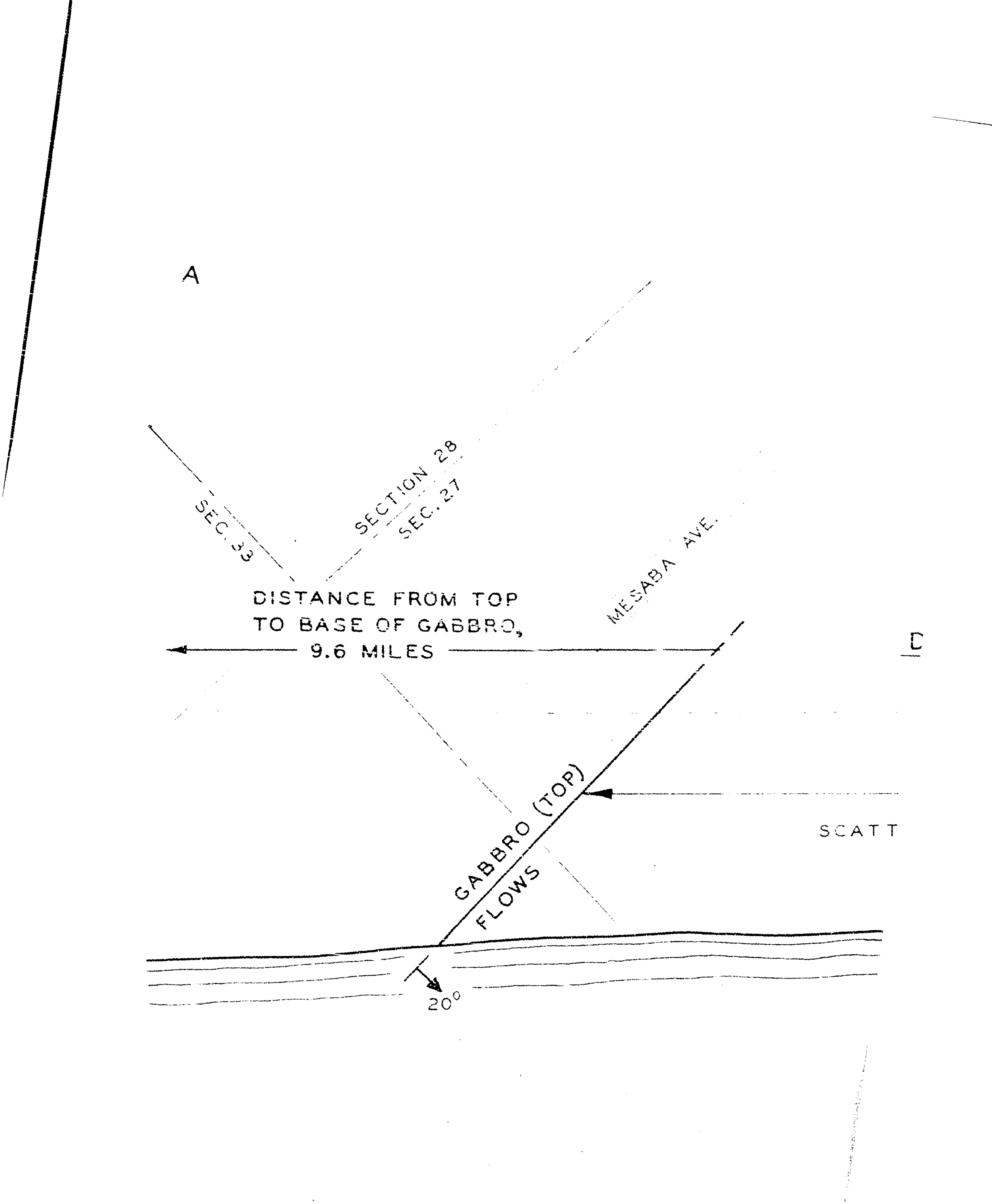
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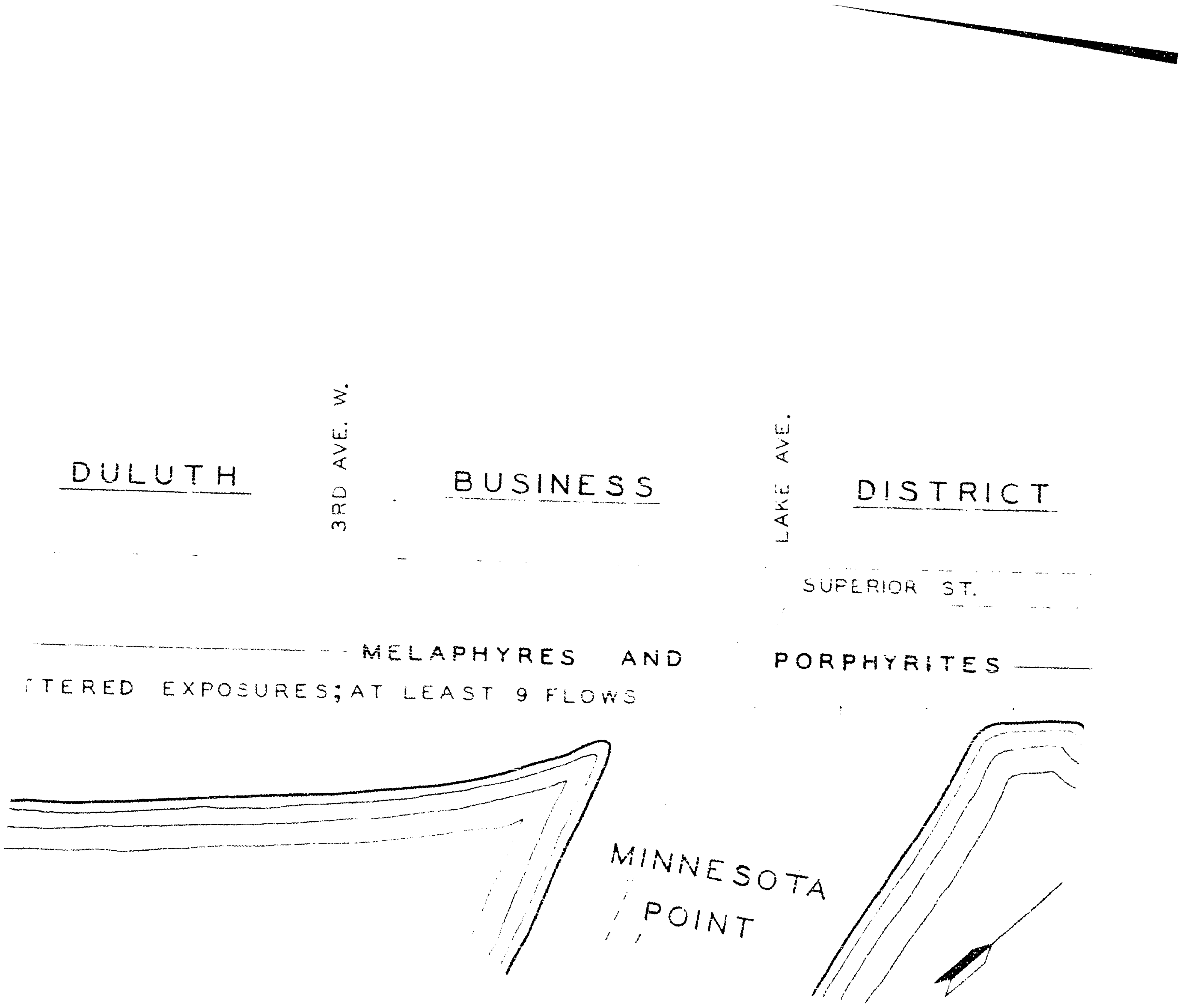
DULUTH
3RD AVE. W.
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MELAPHYRES AND PORPHYRITES
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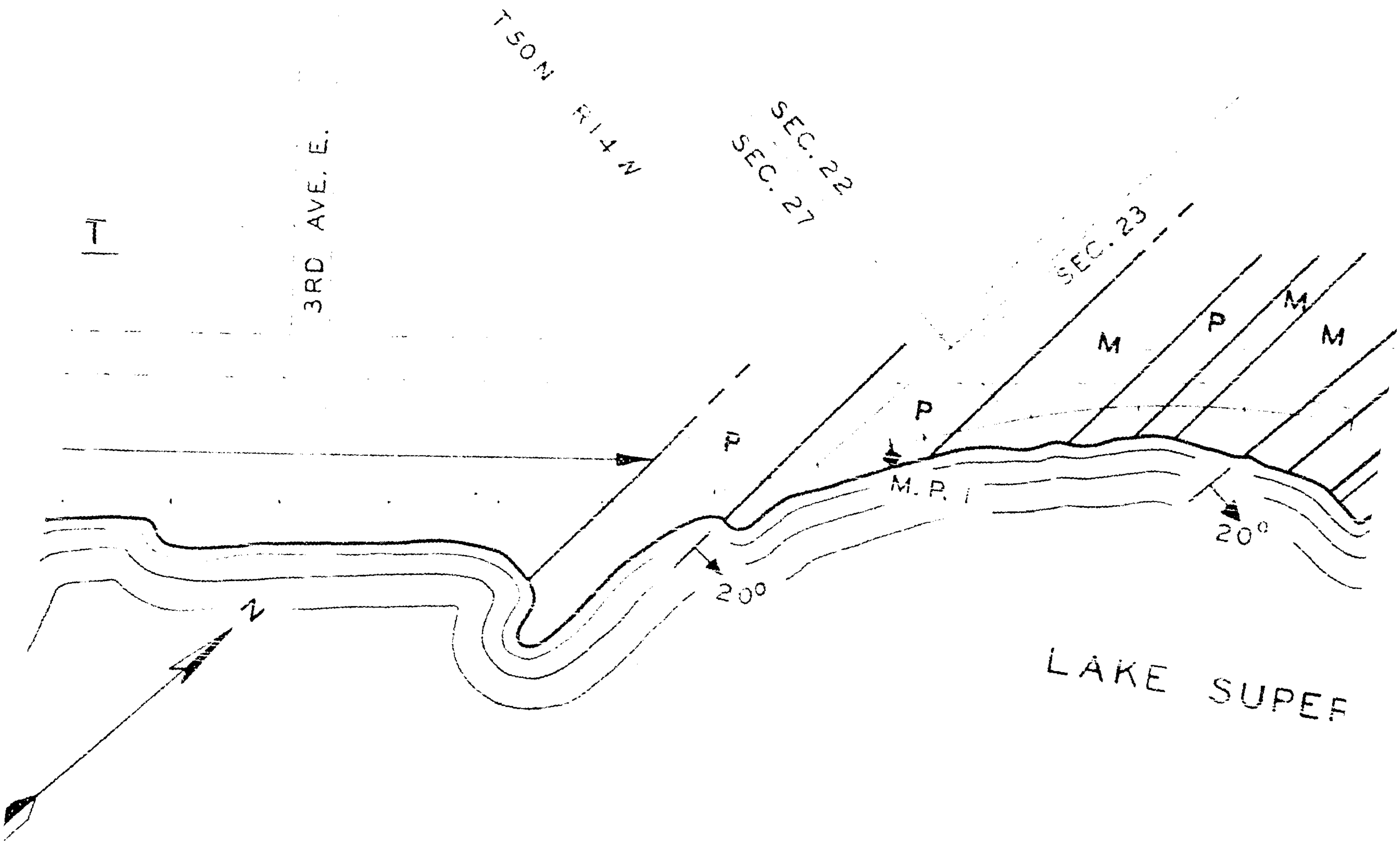
MINNESOTA POINT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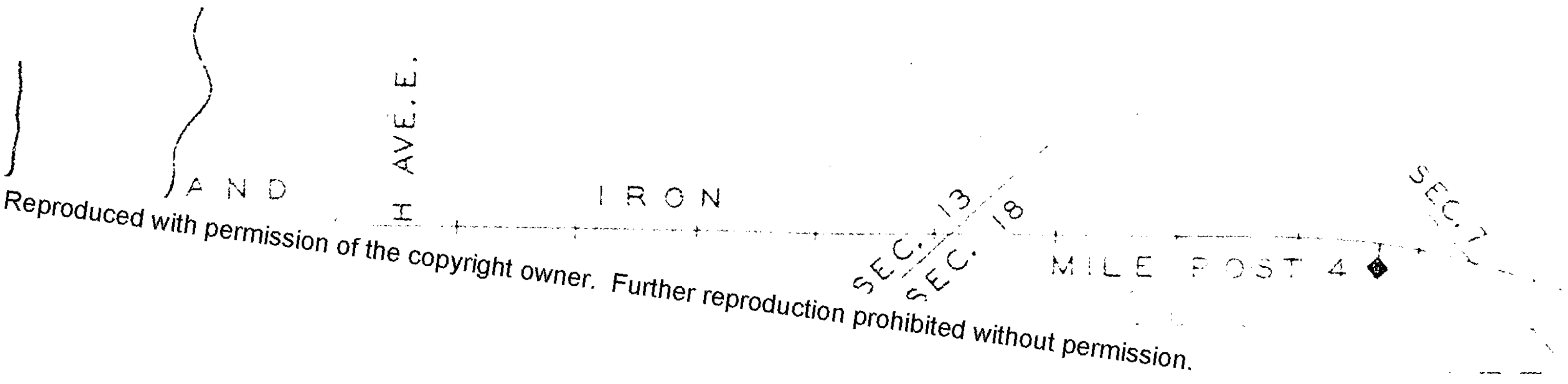
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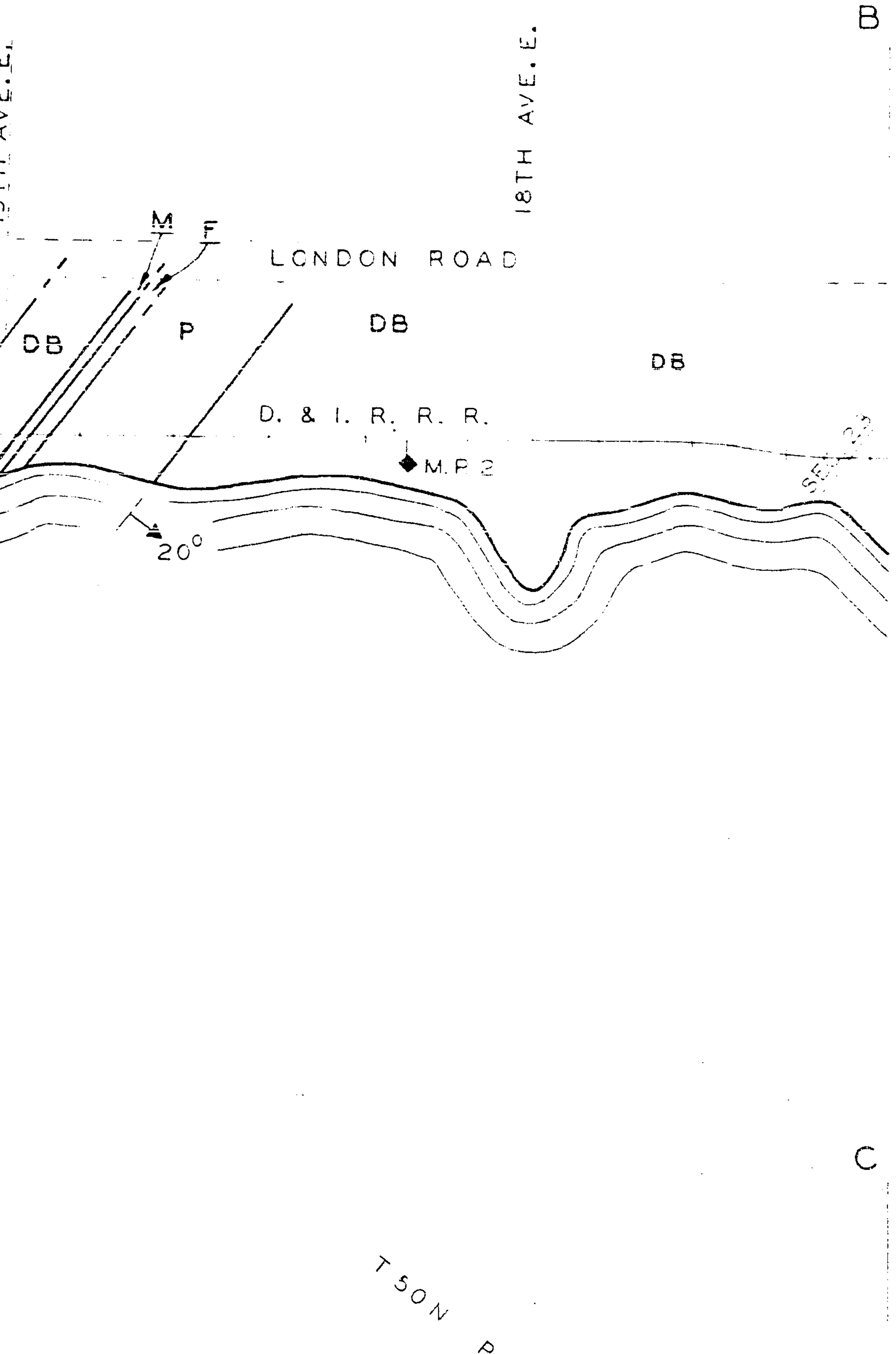
PLATE 6



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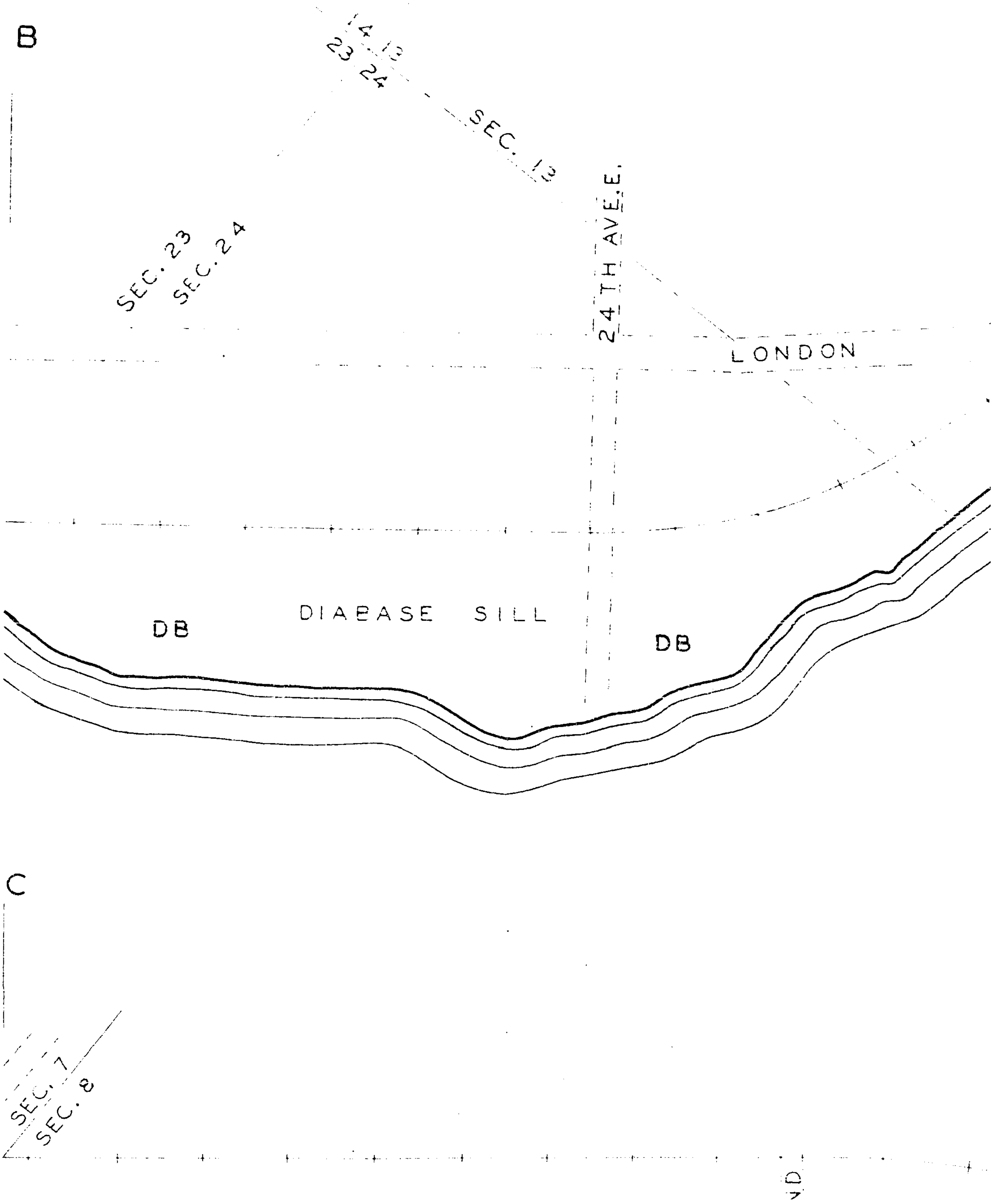
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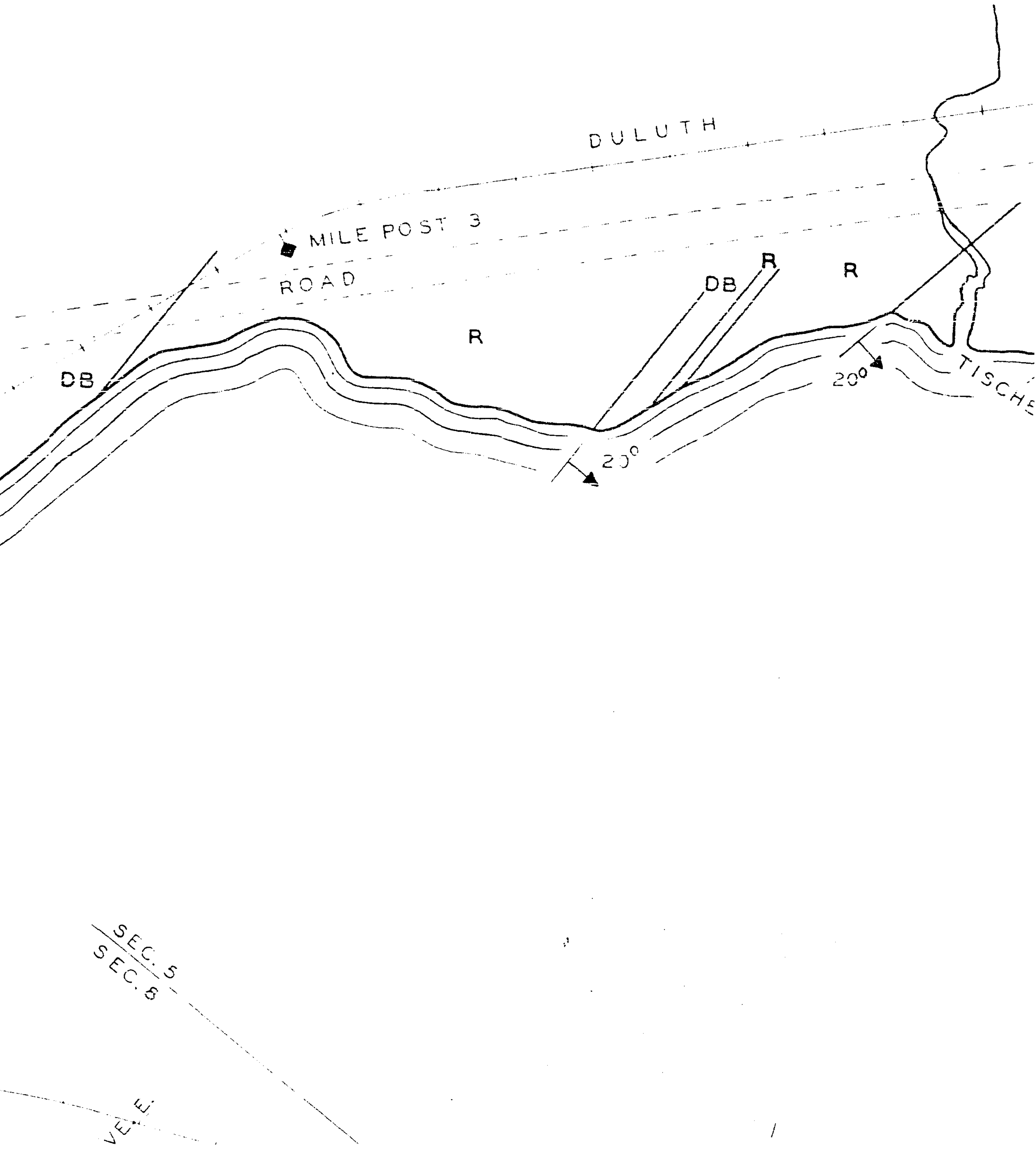
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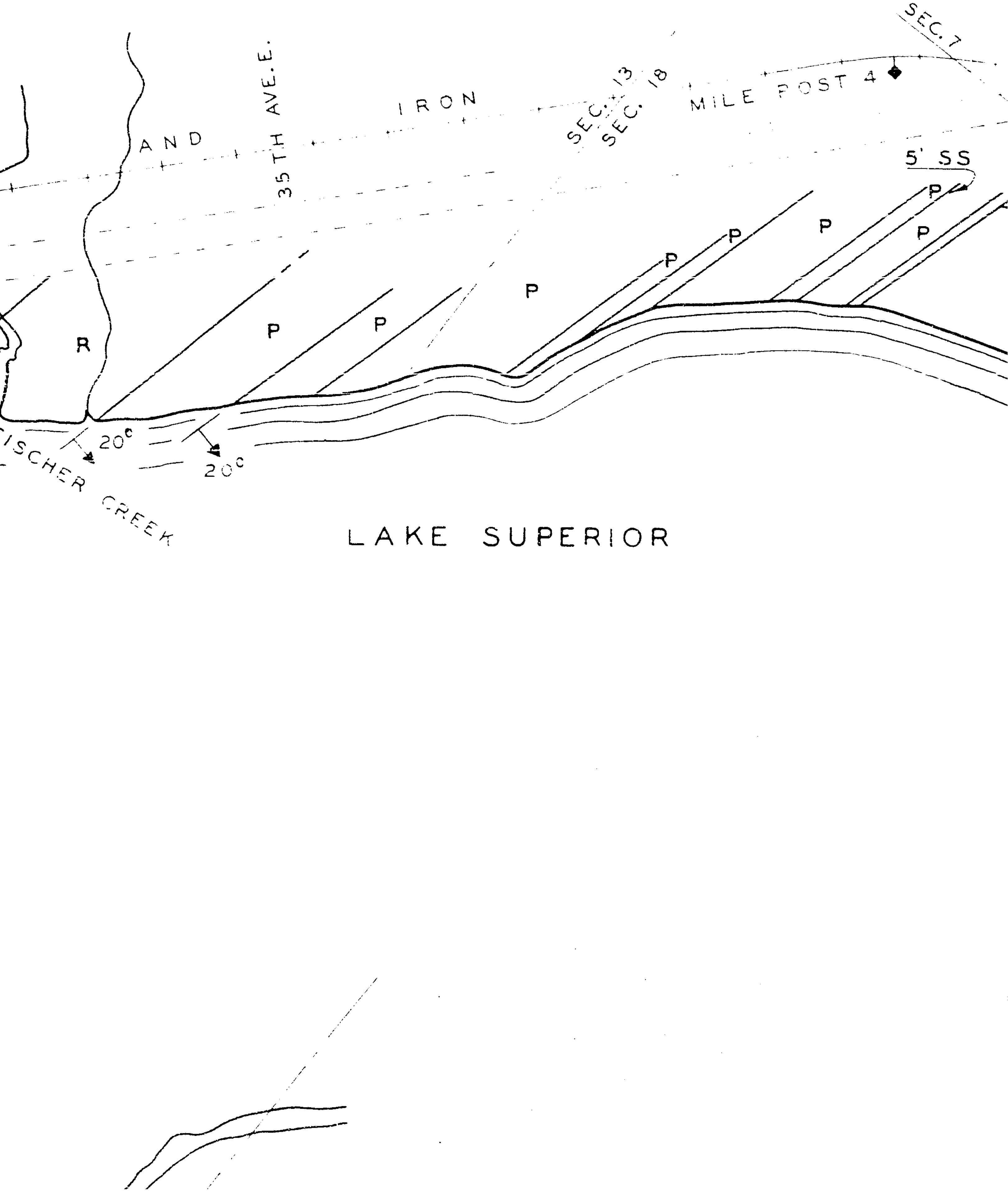
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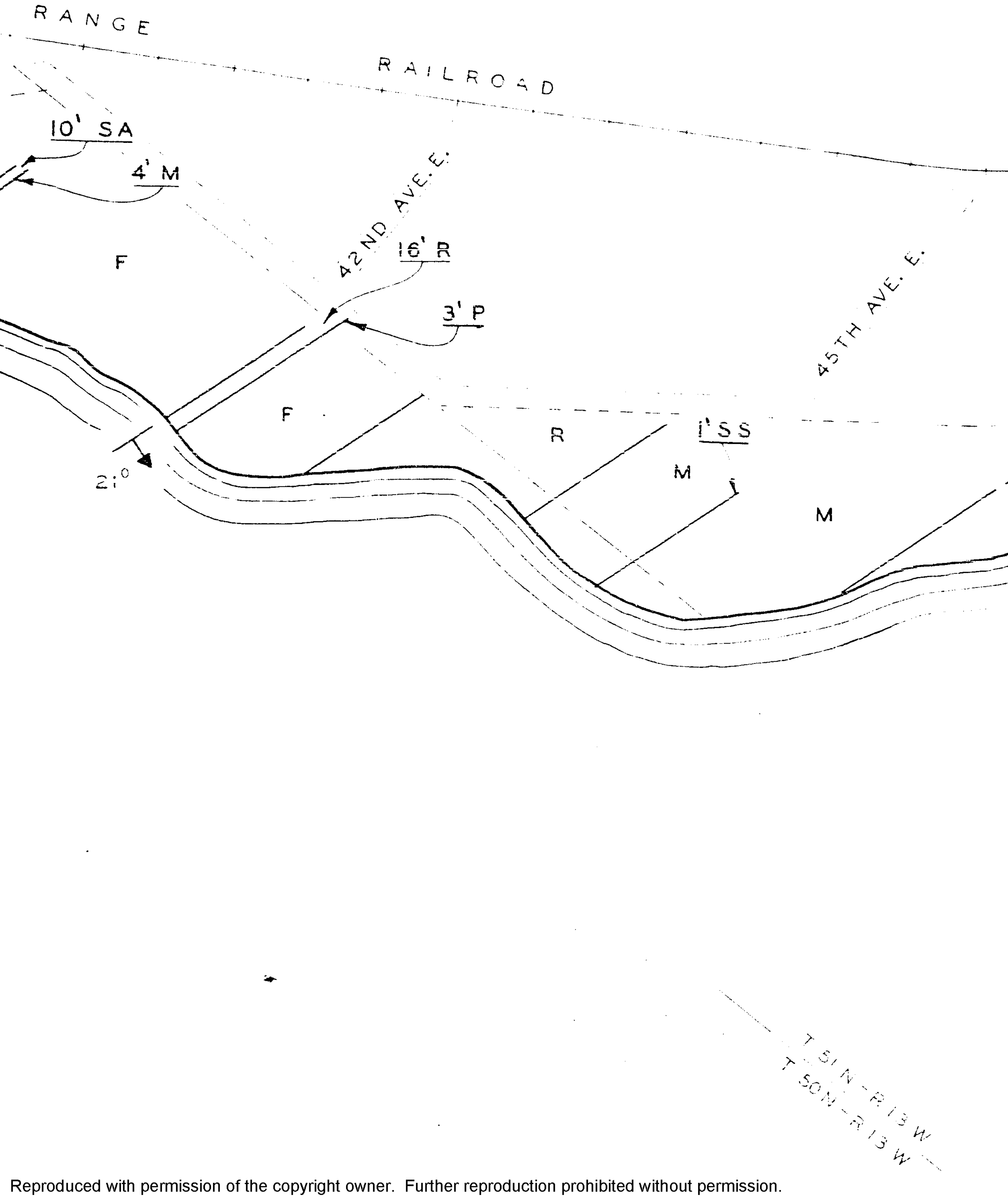
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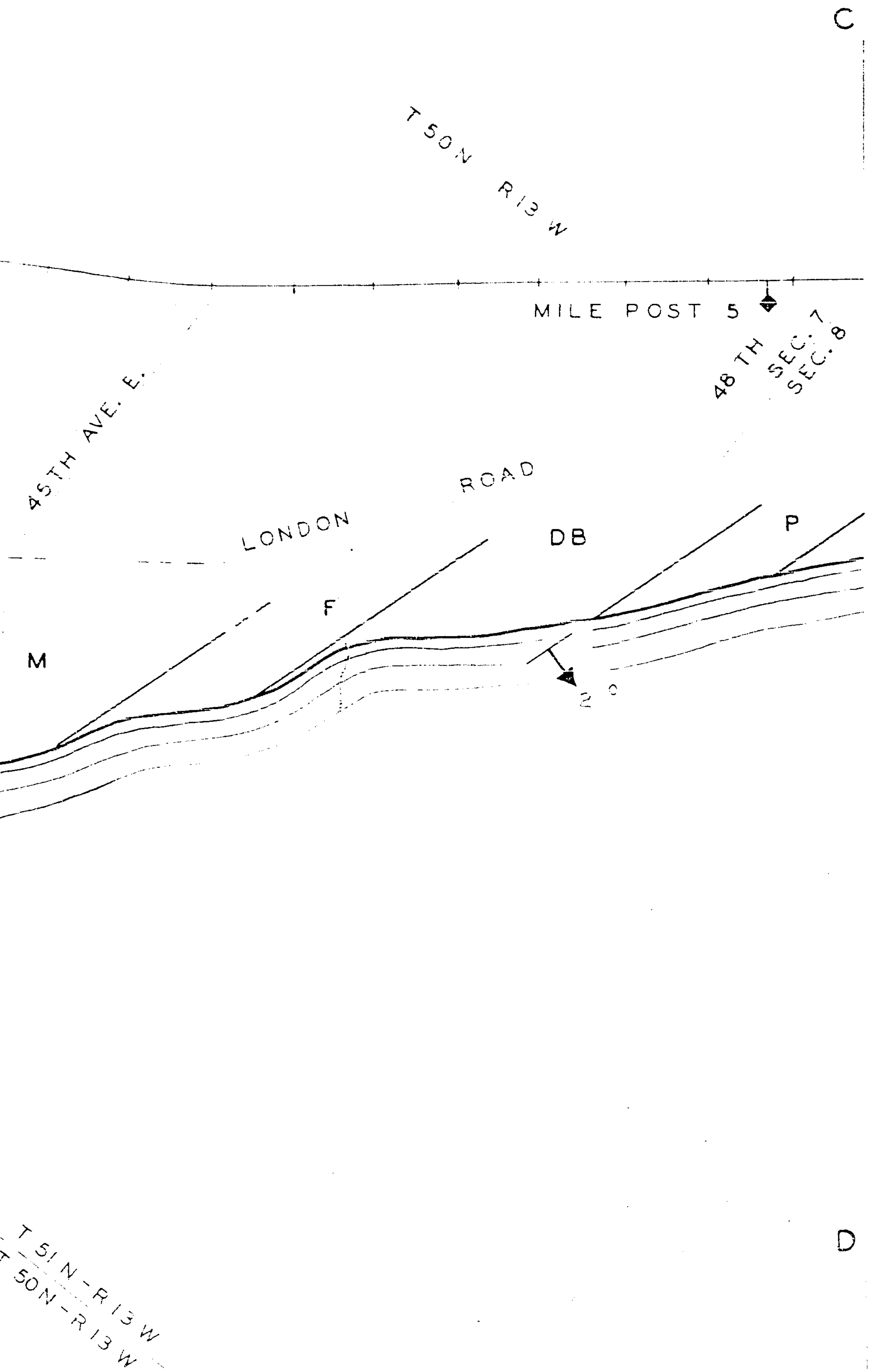
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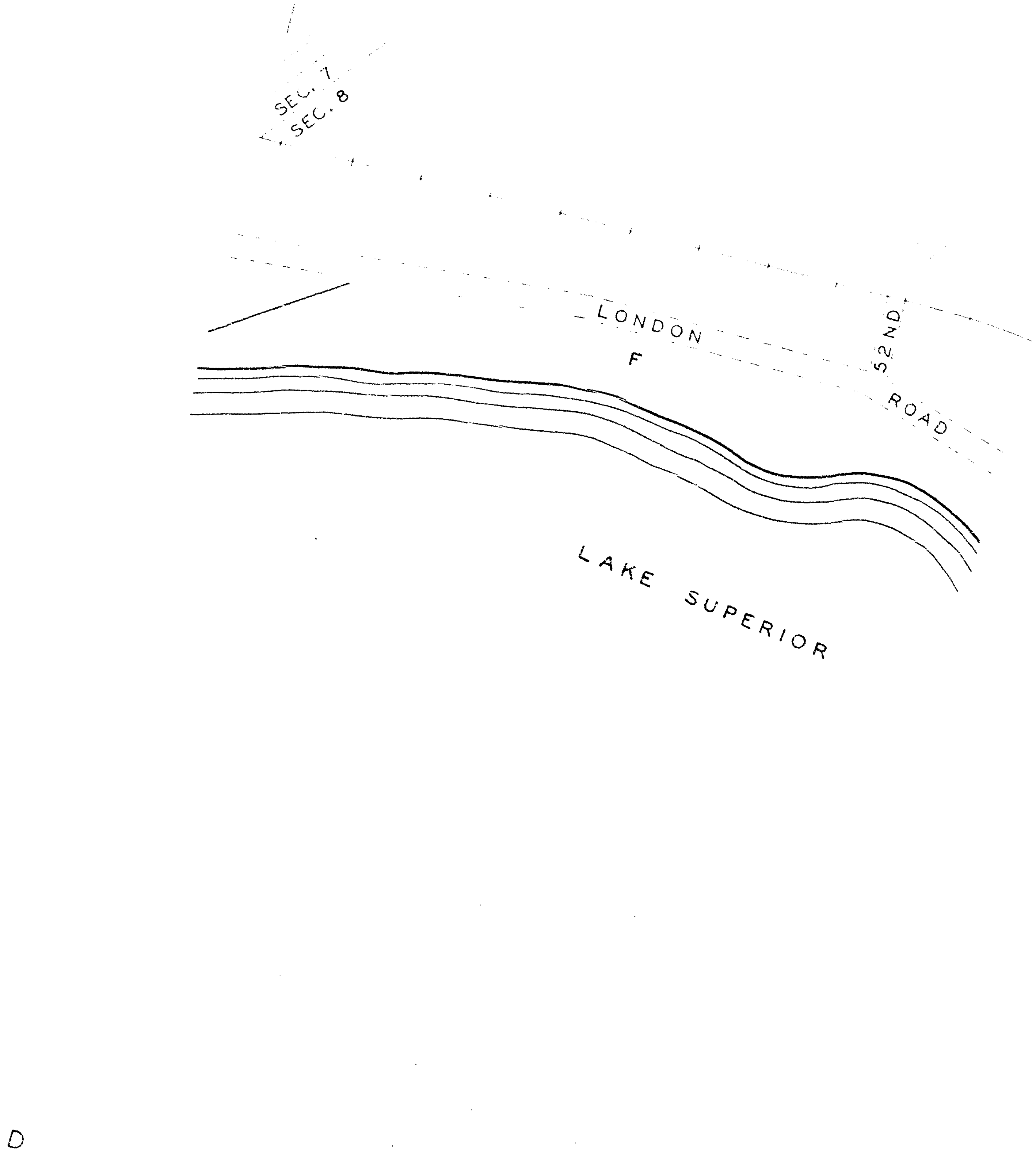
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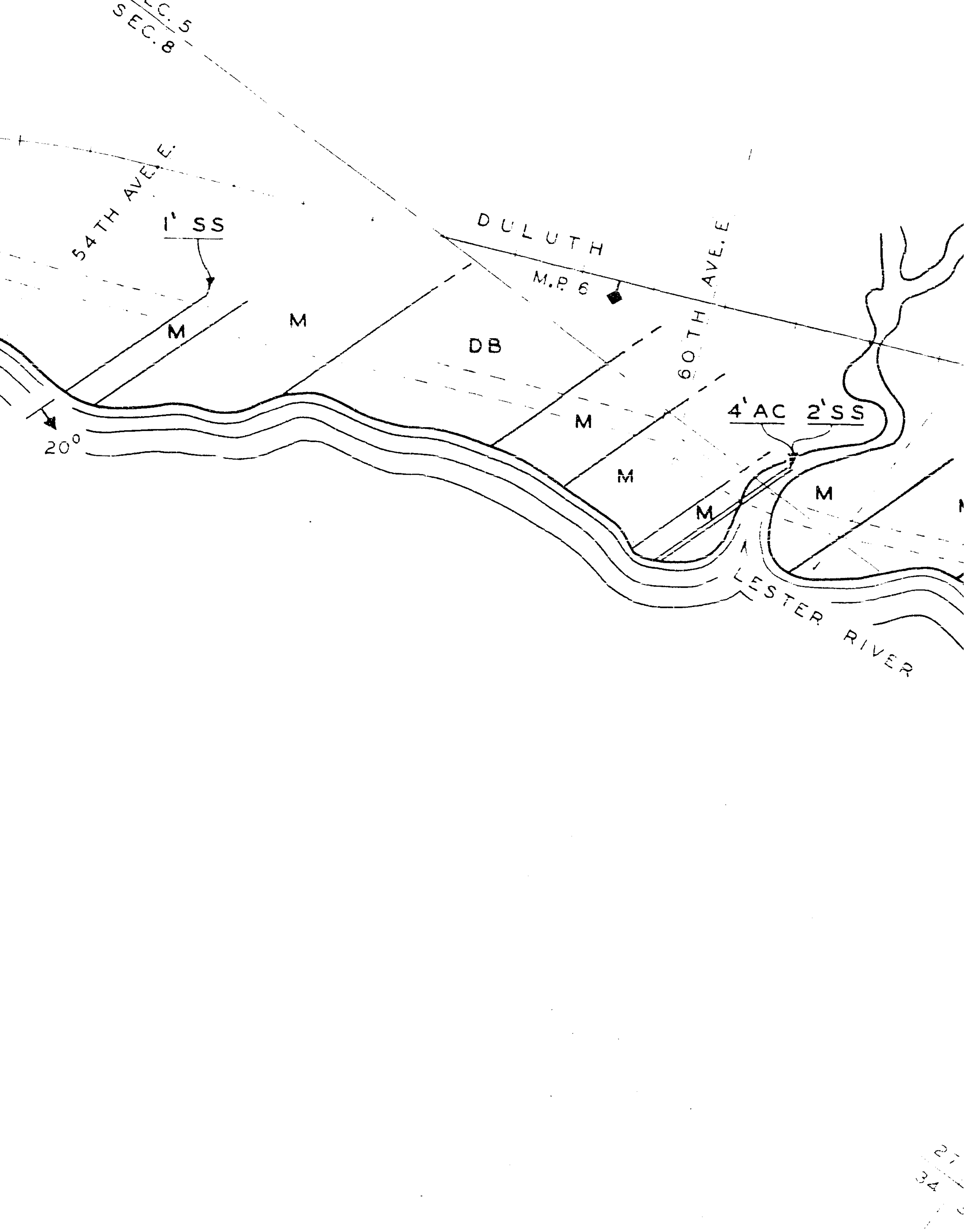
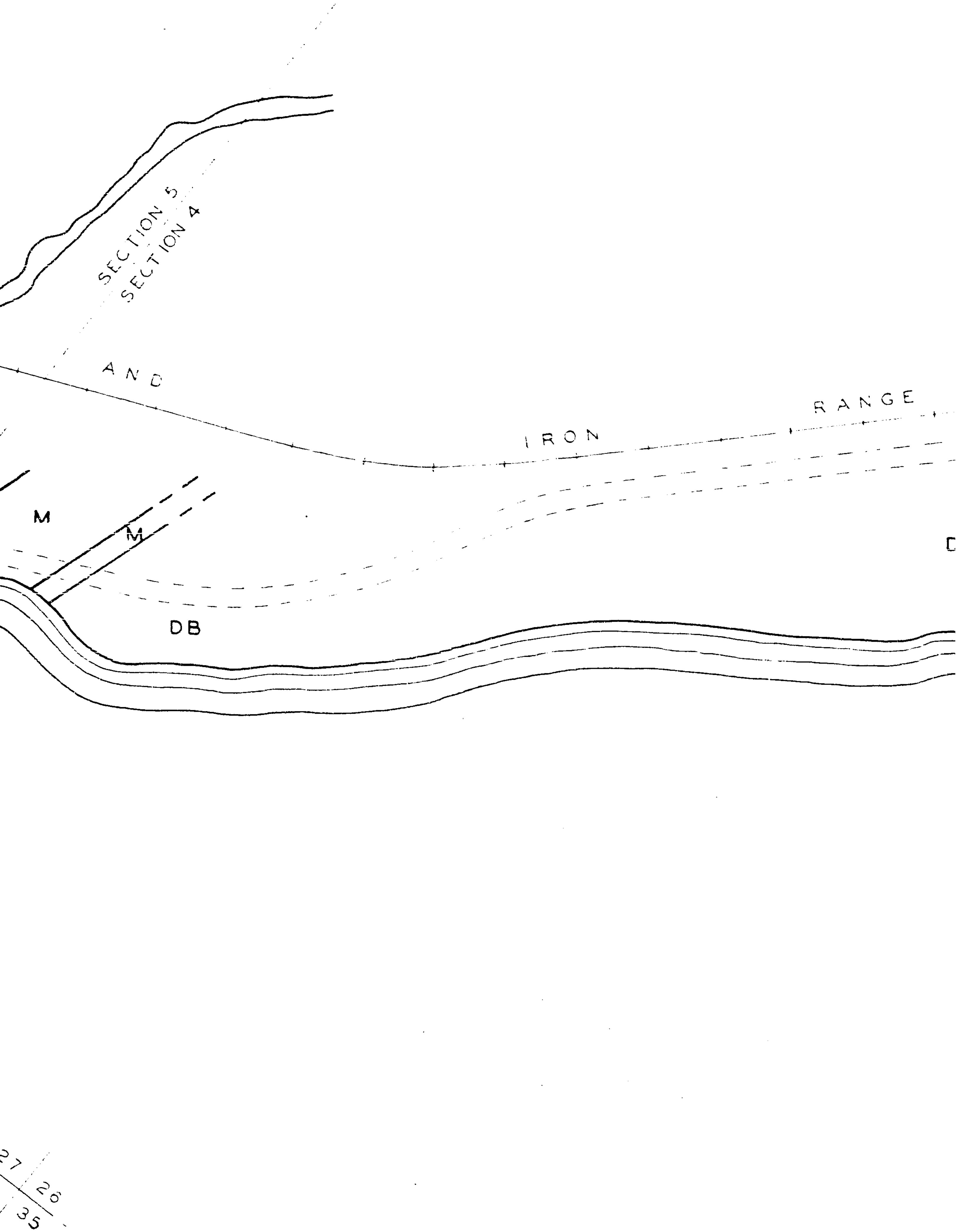
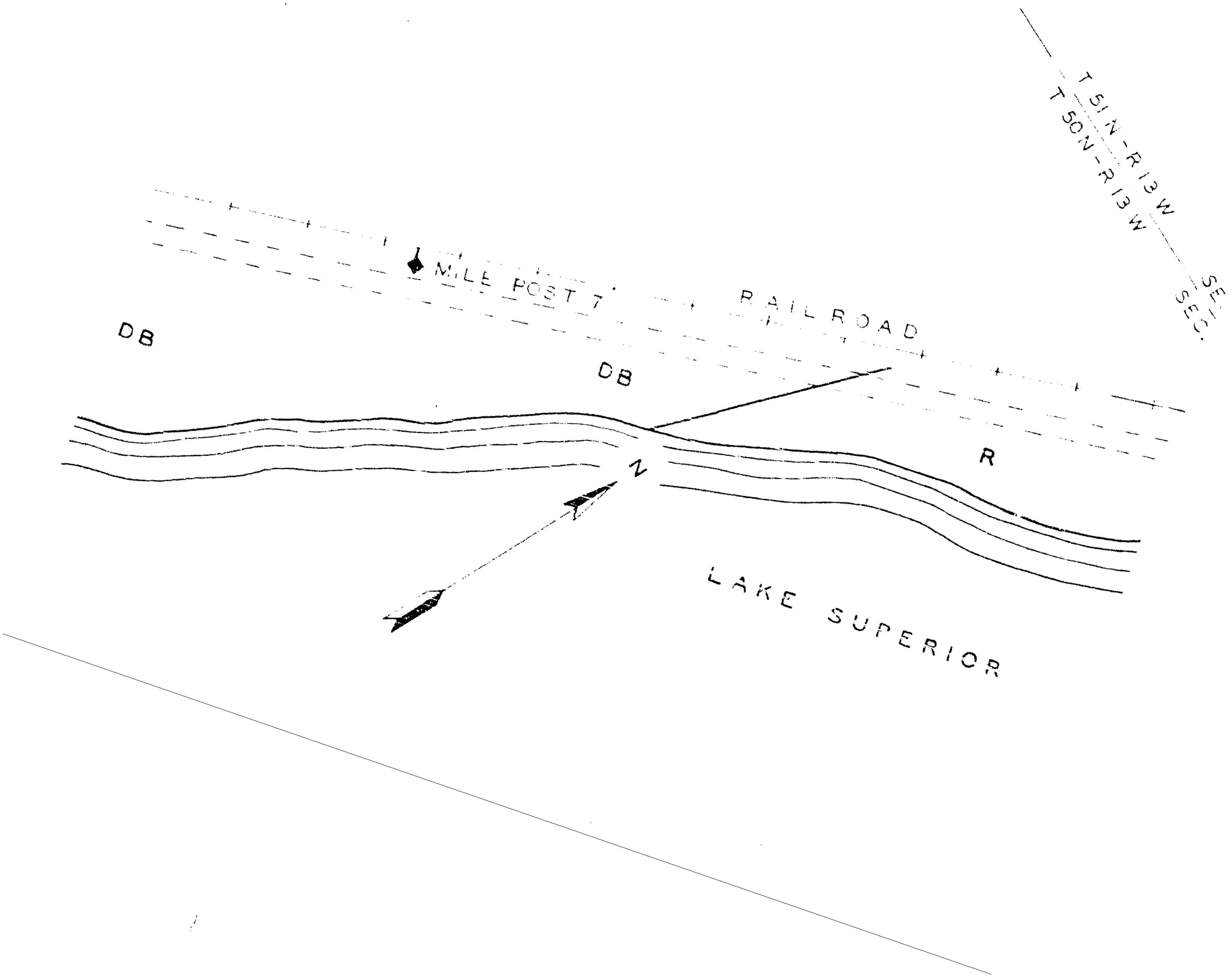
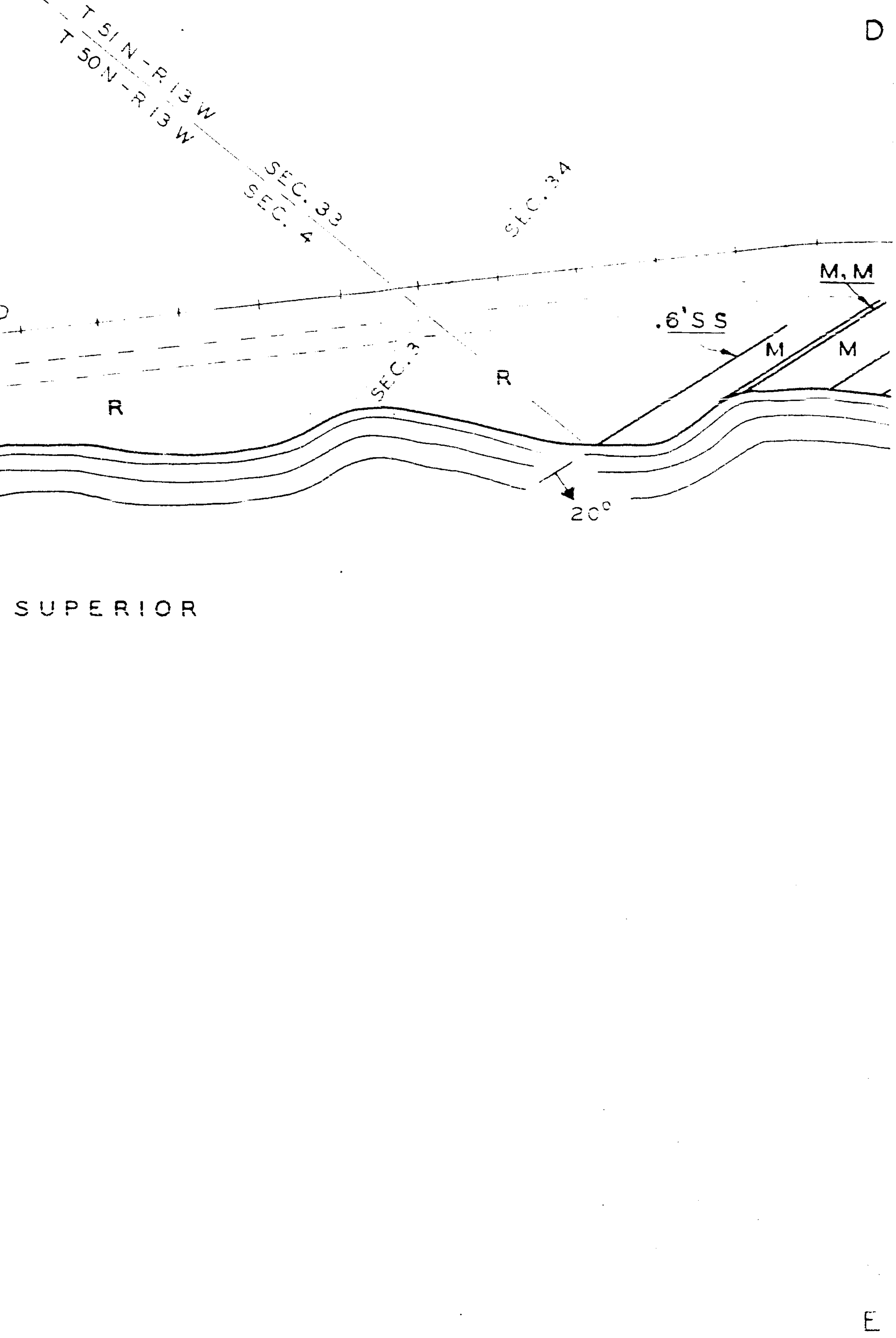
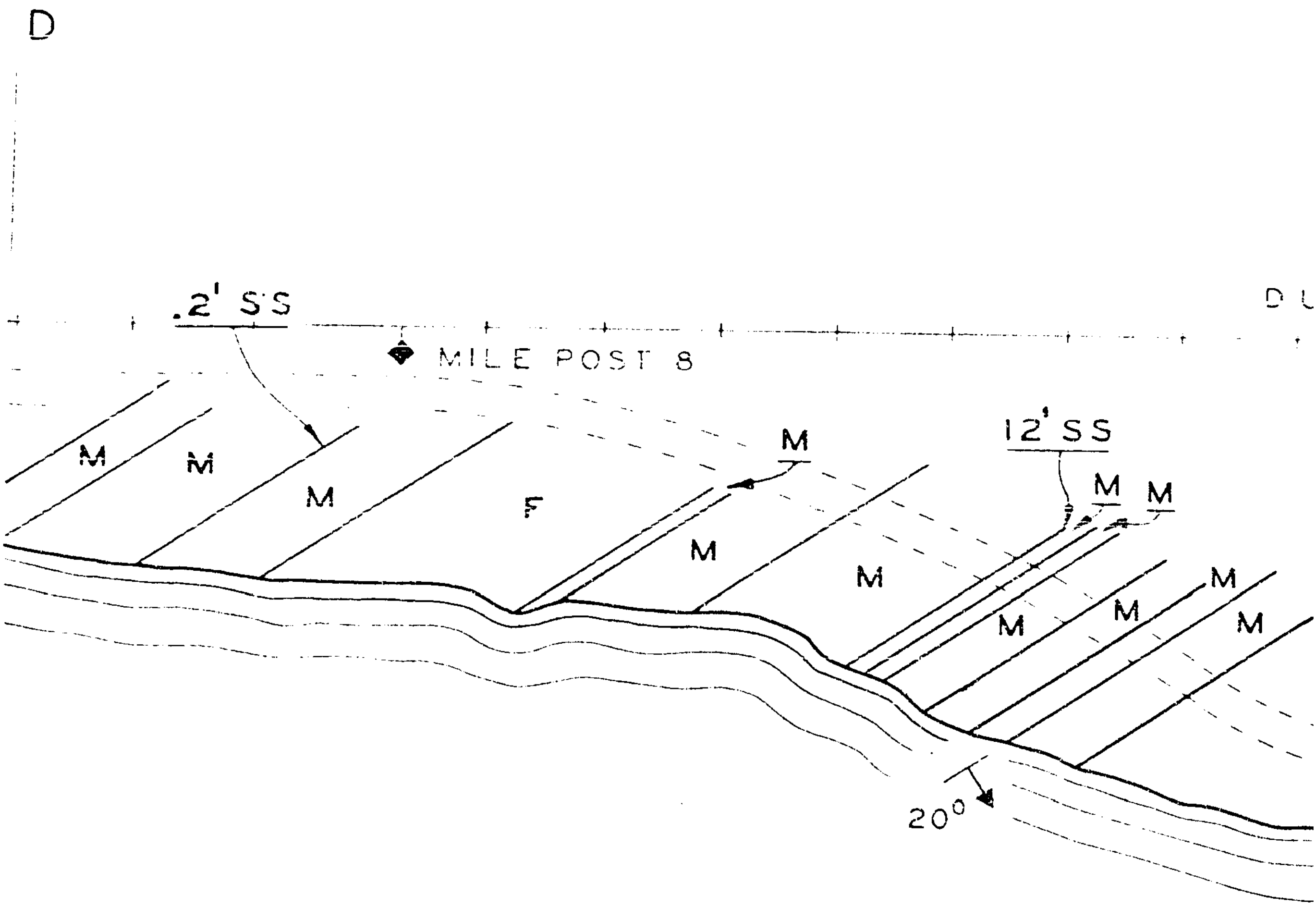
LAKE SUPERIOR
D

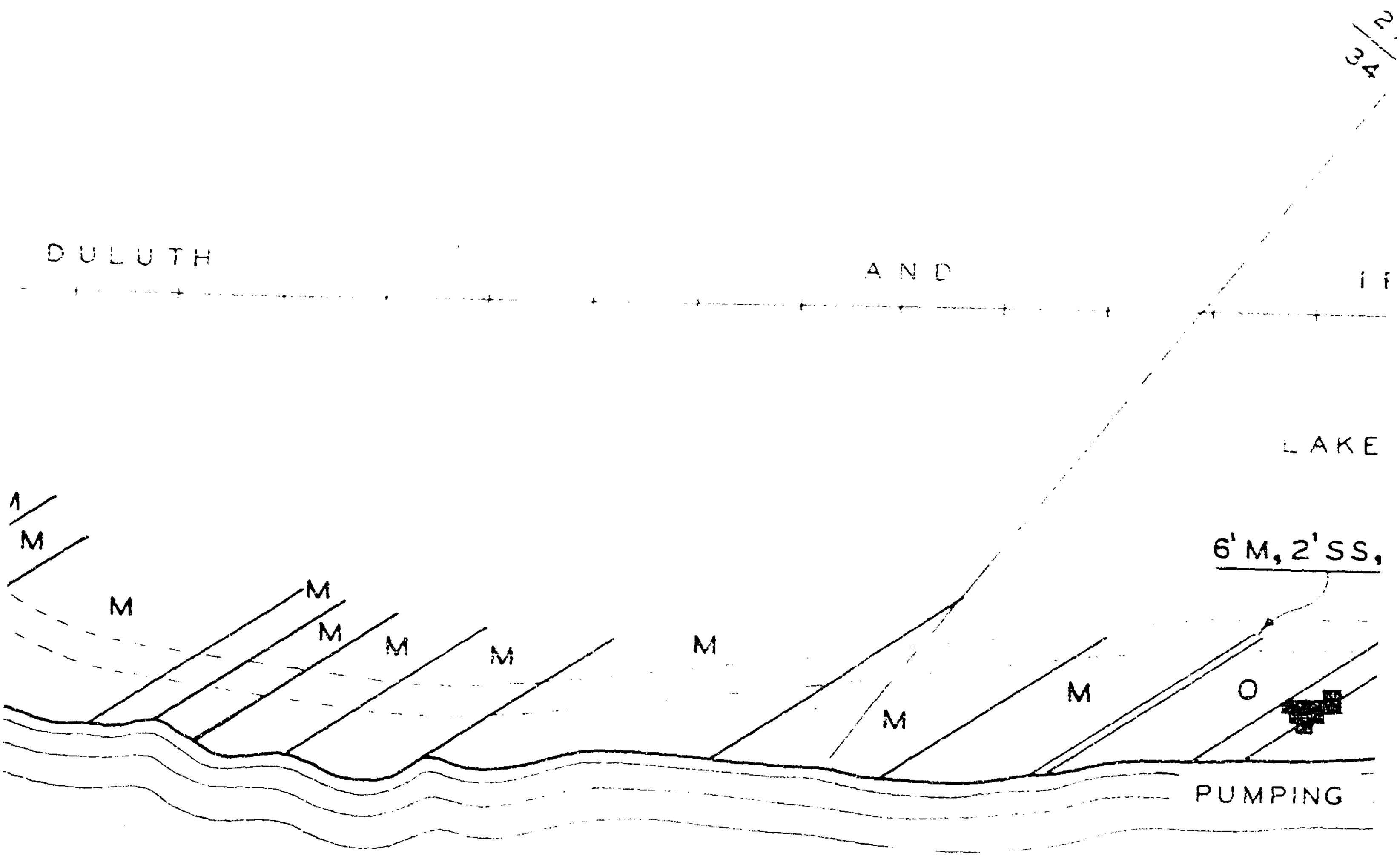

SEC. 5
SEC. 8
54TH AVE. E.
1' SS
M
M
DB
DULUTH
M.P. 6
60TH AVE. E
M
M
M
4' AC
2' SS
M
20°
LESTER RIVER
21
34

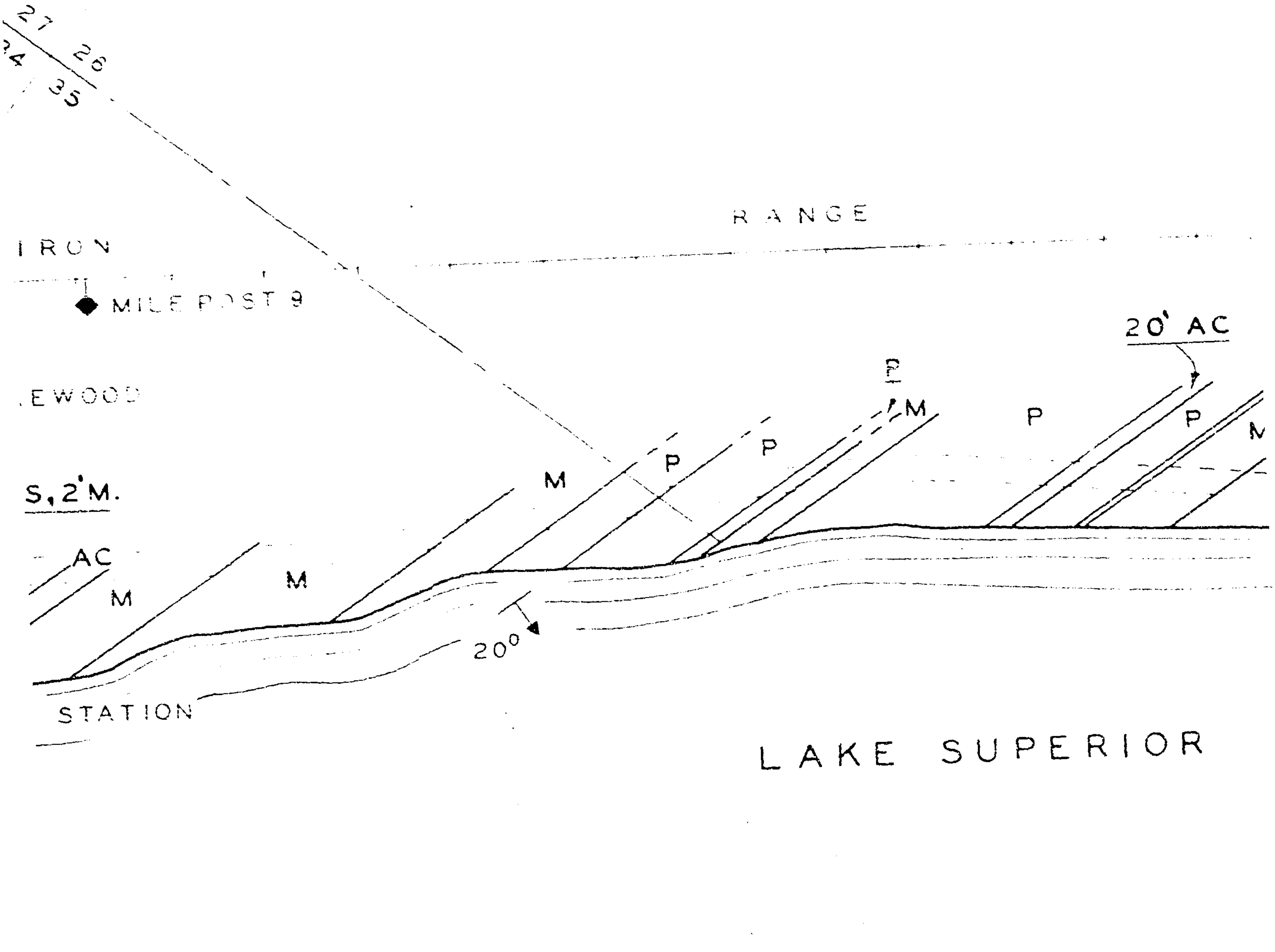

SECTION 5
SECTION 4
AND
IRON
RANGE
M
M
DB
D
27
26
35

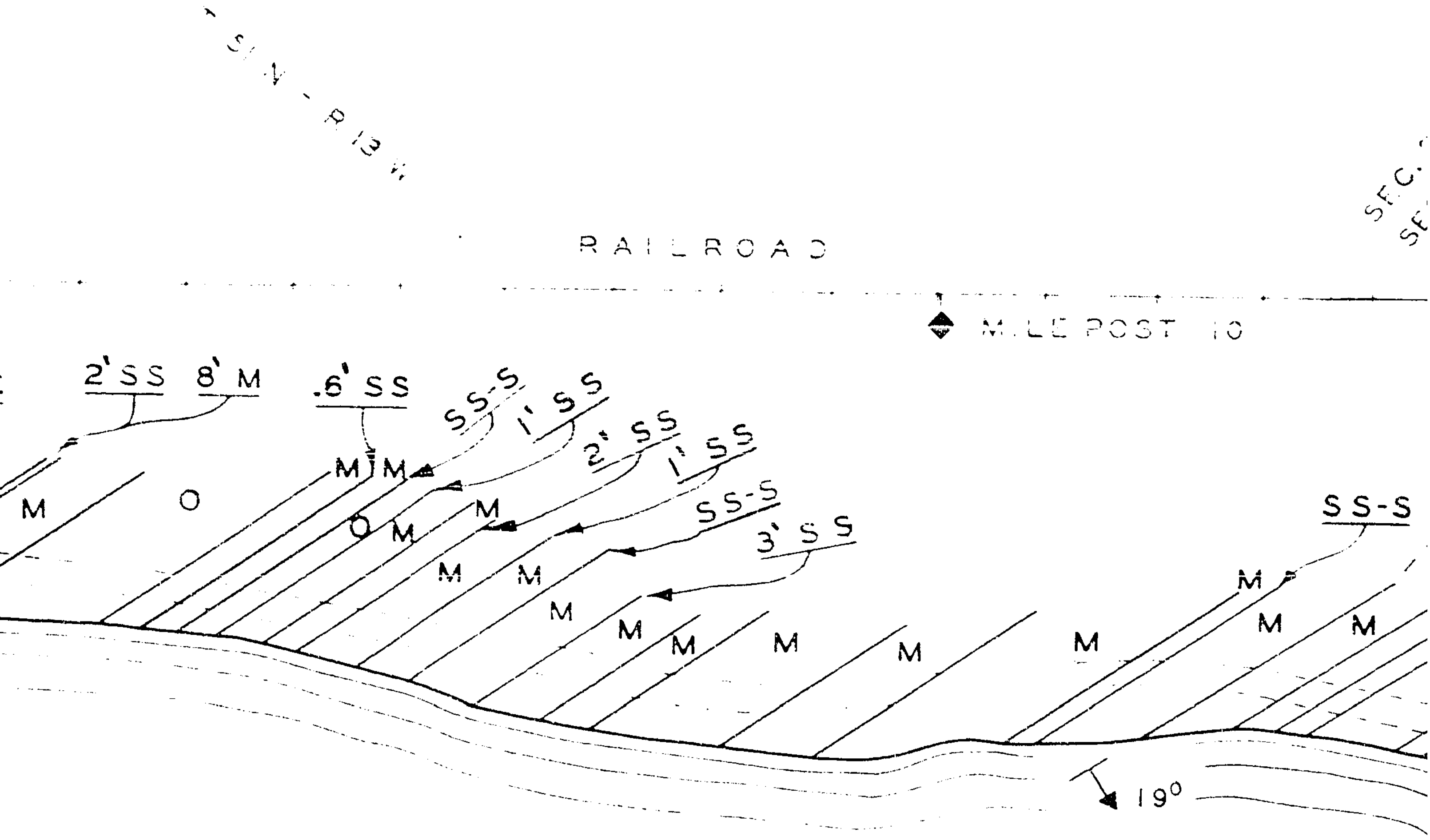

T 51 N - R 13 W
T 50 N - R 13 W
SEC.
SEC.
MILE POST 7
RAILROAD
DB
DB
R
N
LAKE SUPERIOR

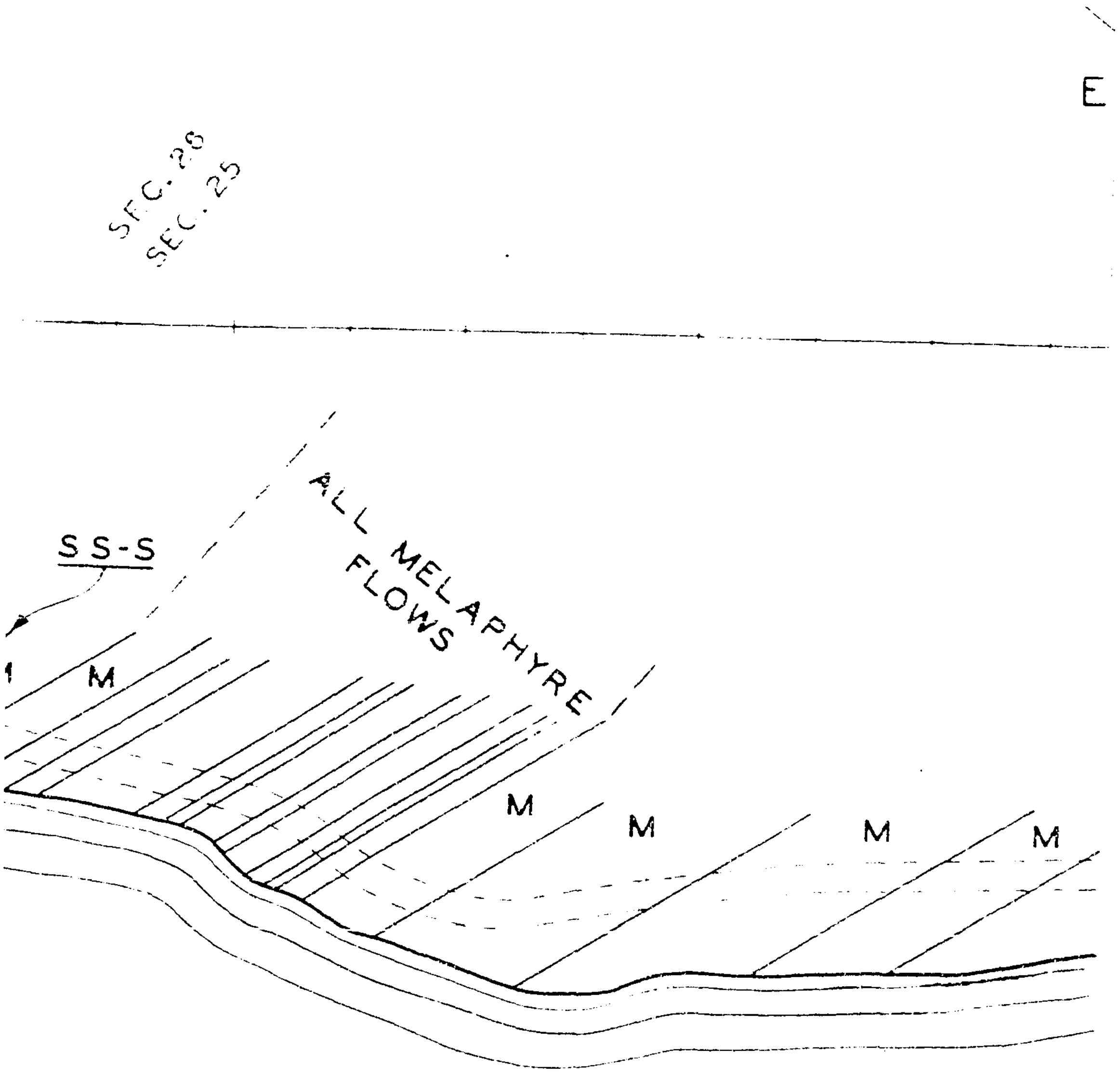

D
T 51 N - R 13 W
T 50 N - R 13 W
SEC. 33
SEC. 4
SEC. 34
SEC. 3
M, M
.6' S S
M
M
R
R
20°
SUPERIOR
E

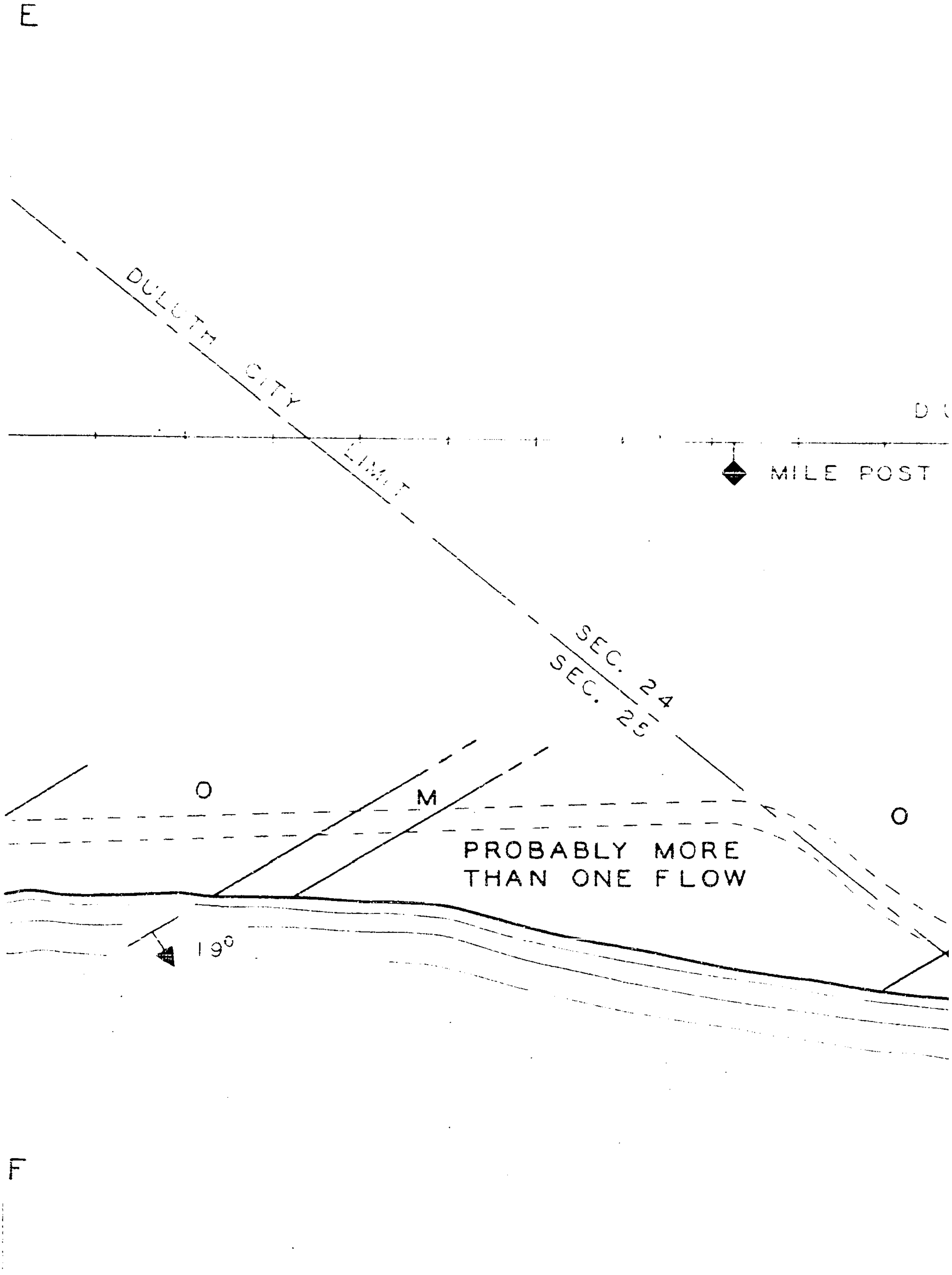

D
.2' SS
MILE POST 8
12' SS
D L
M
M
M
F
M
M
M
M
M
M
M
M
M
M
M
20°

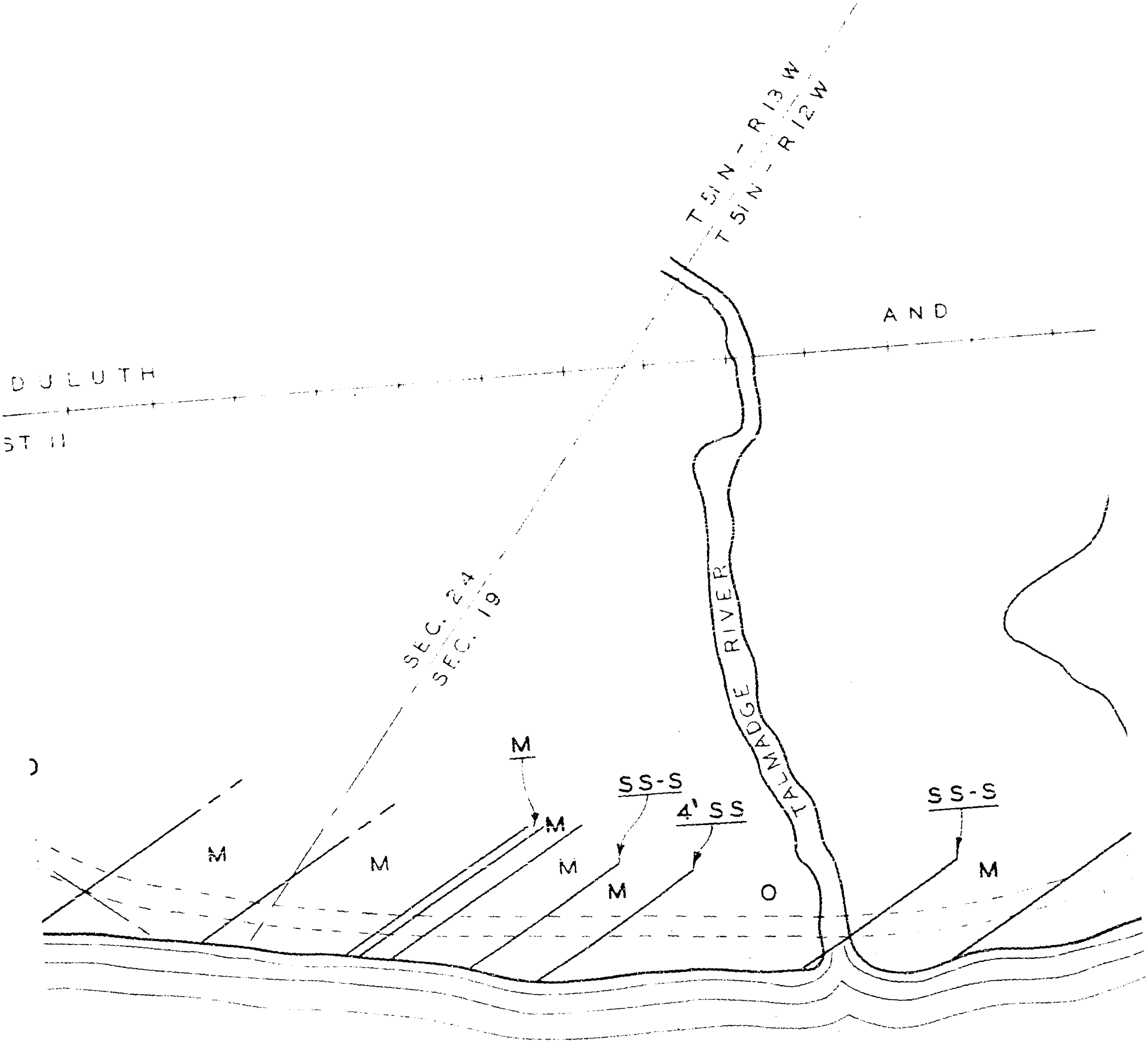

DULUTH
AND
I R
3/4
2
LAKE
1
M
6'M, 2'SS,
M
M
M
M
M
M
M
M
O
PUMPING

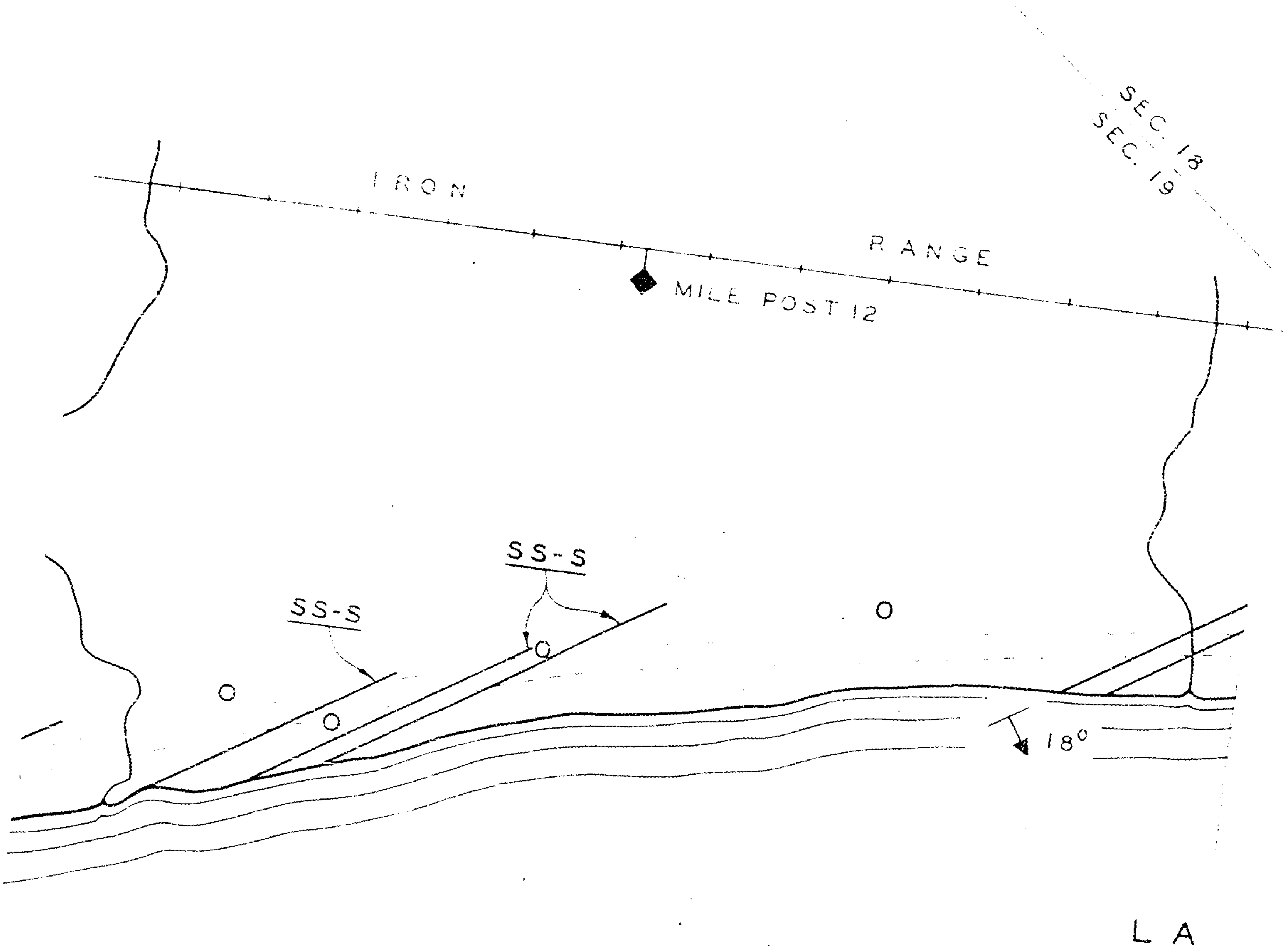

27
26
34
35
RANGE
IRON
MILE POST 9
EWOOD
S, 2' M.
AC
M
M
M
M
P
P
P
M
P
P
M
20' AC
20°
STATION
LAKE SUPERIOR


5 N - R 13 W
RAILROAD
MILE POST 10
SEC.
2' SS
8' M
.6' SS
SS-S
1' SS
2' SS
1' SS
SS-S
3' SS
SS-S
M
O
M M
O M
M
M
M
M
M
M
M
M
M
M
M
M
M
19°


E
SEC. 26
SEC. 25
ALL MELAPHYRE FLOWS
SS-S
M
M
M
M
M


E
DULUTH CITY LIMIT
D
MILE POST
SEC. 24
SEC. 25
O
M
O
PROBABLY MORE THAN ONE FLOW
19°
F


T 51 N - R 13 W
T 51 N - R 12 W
DULUTH
AND
ST ..
SEC. 24
SEC. 19
TALMADGE RIVER
M
SS-S
4' SS
SS-S
M
M
M
M
M
M
O
M


SEC. 18
SEC. 19
IRON
RANGE
MILE POST 12
SS-S
SS-S
18°
L A

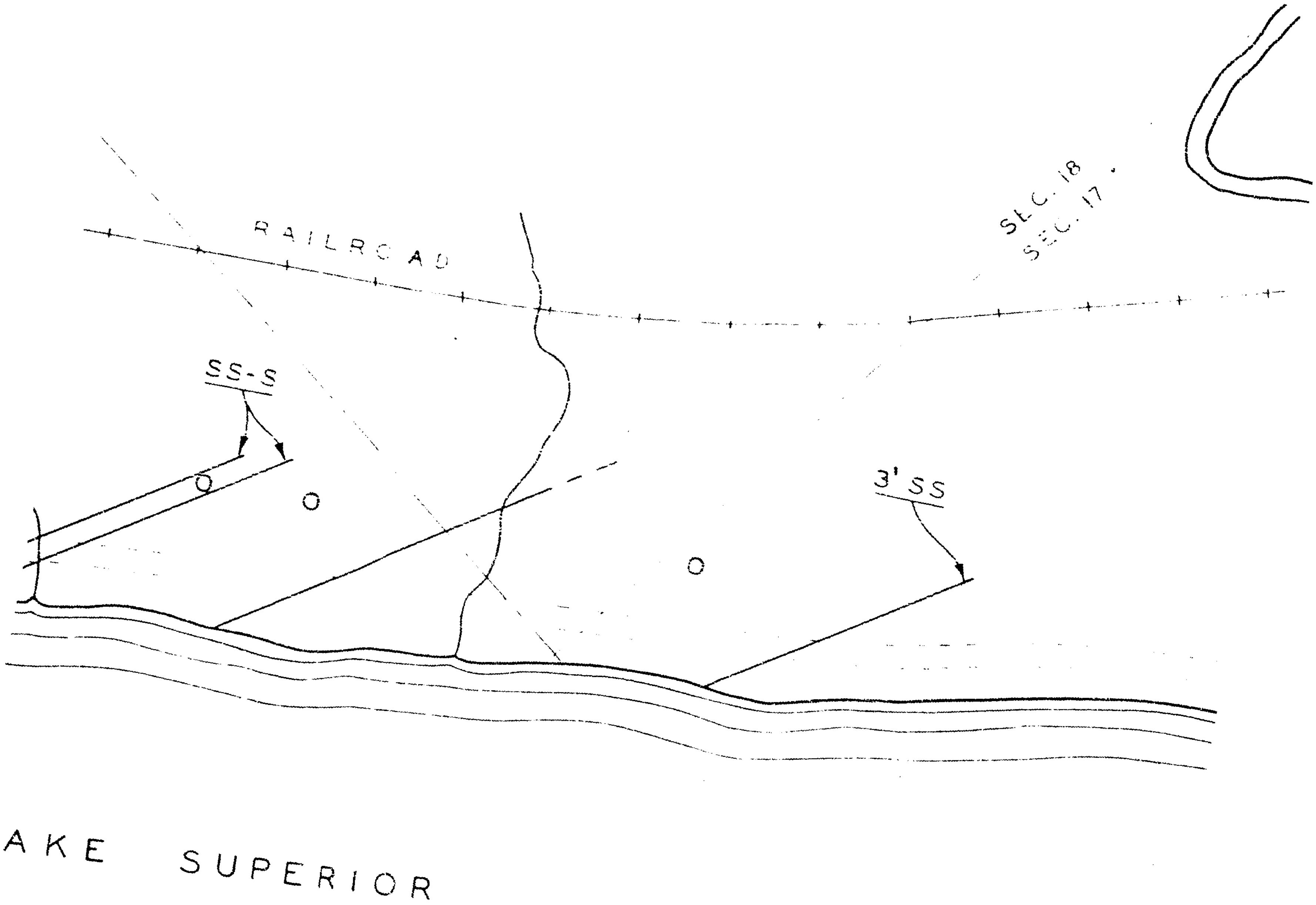
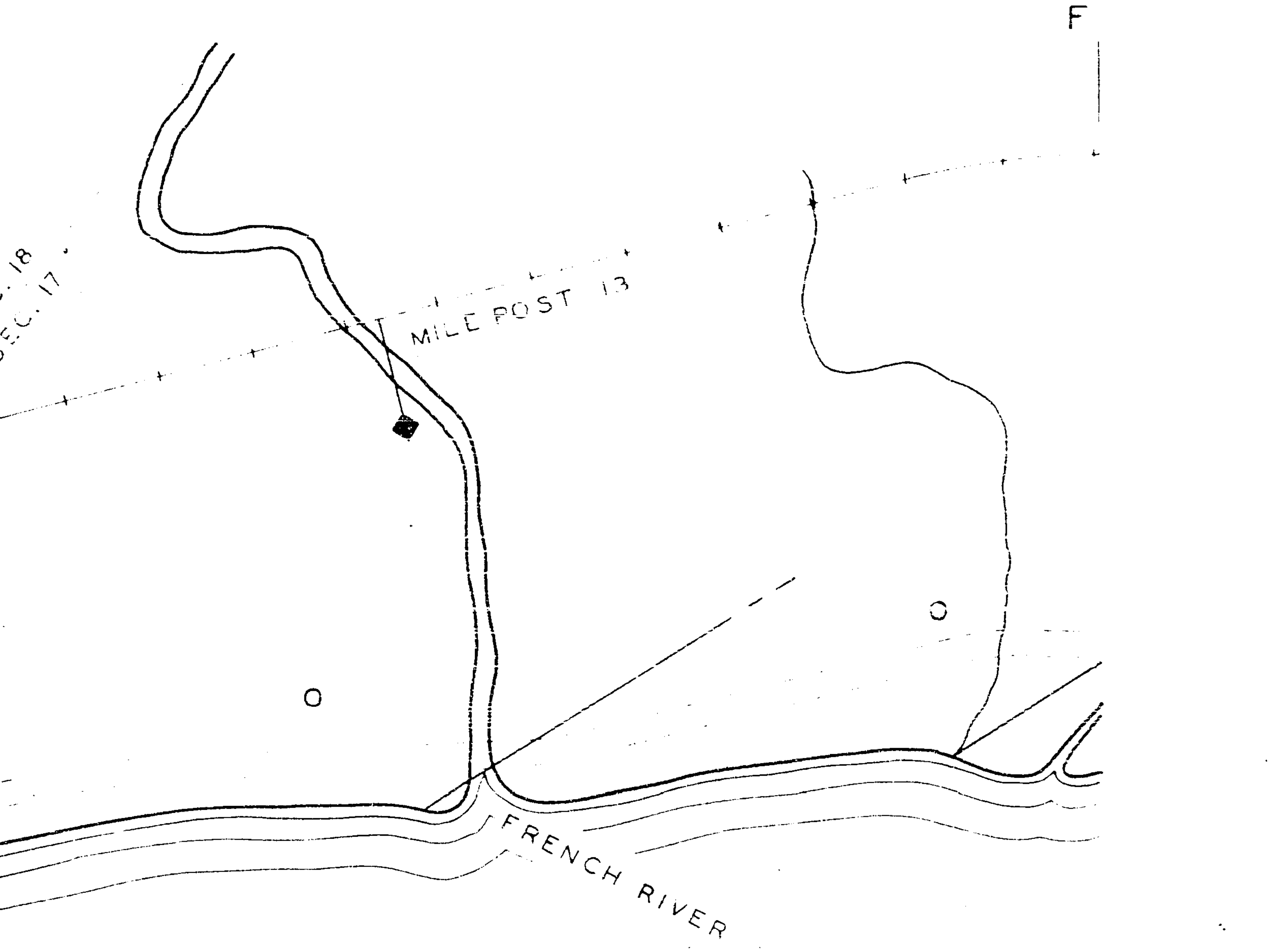
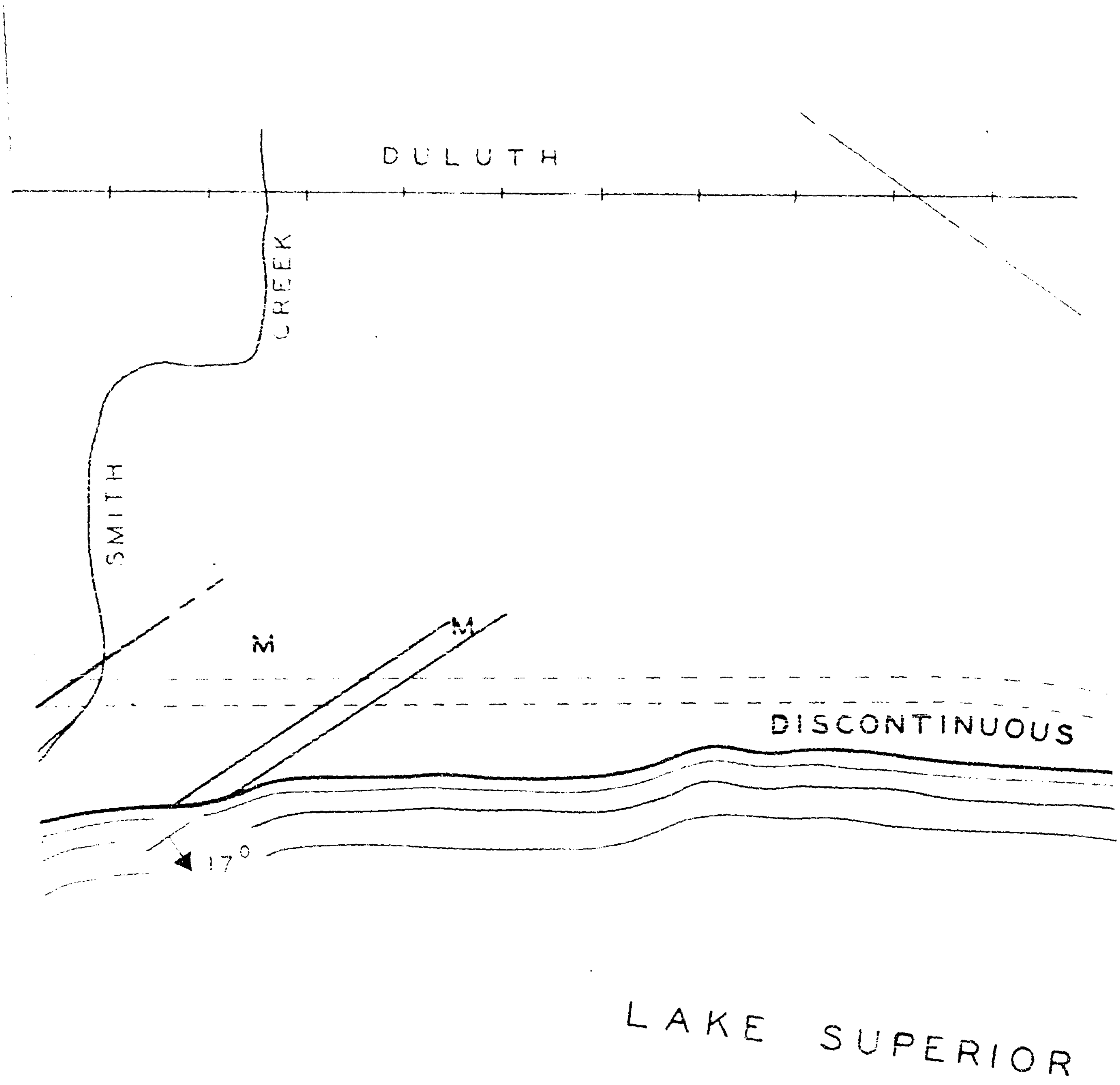
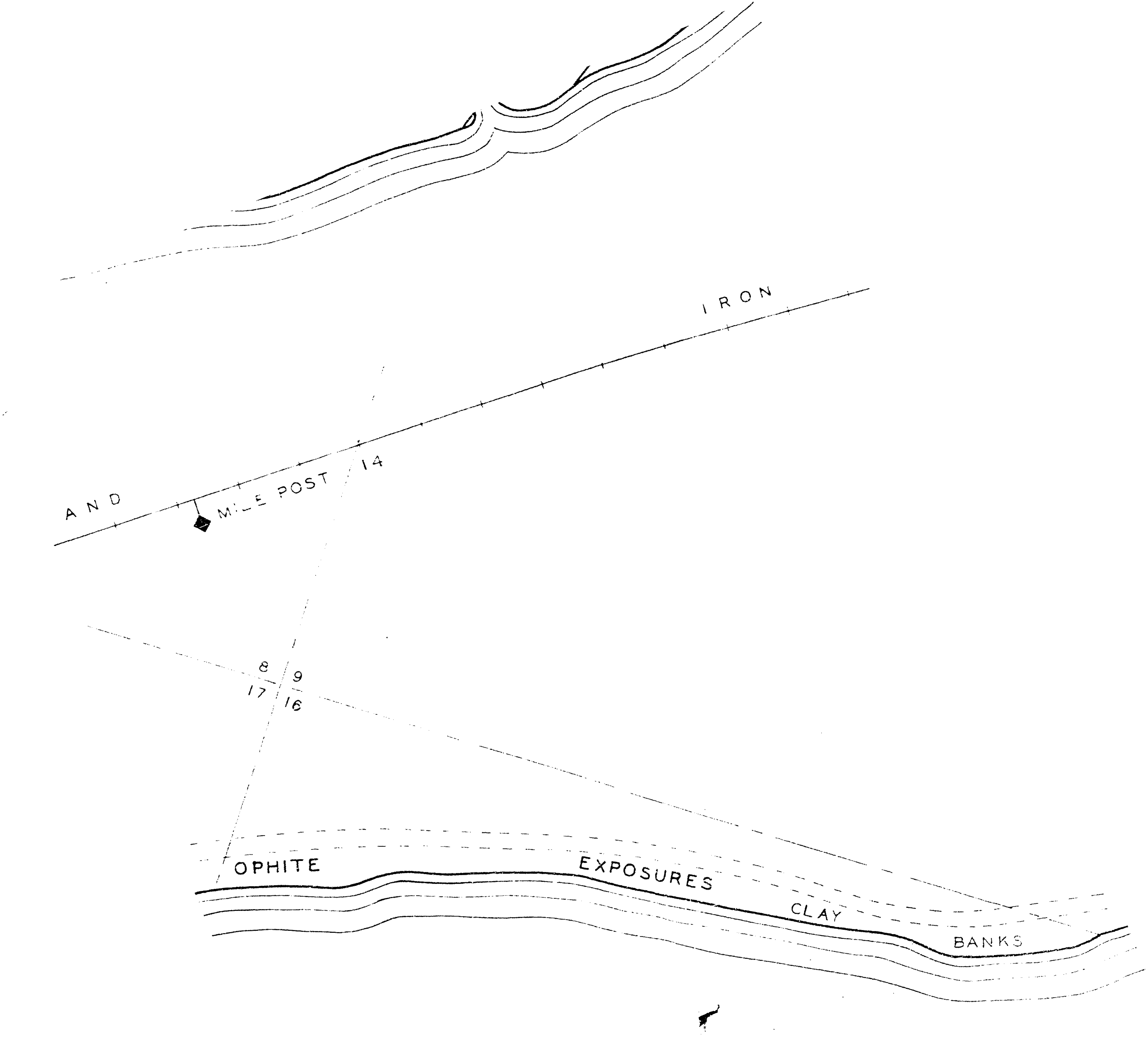

RAILROAD
SEC. 18
SEC. 17
SS-S
3' SS
-AKE SUPERIOR

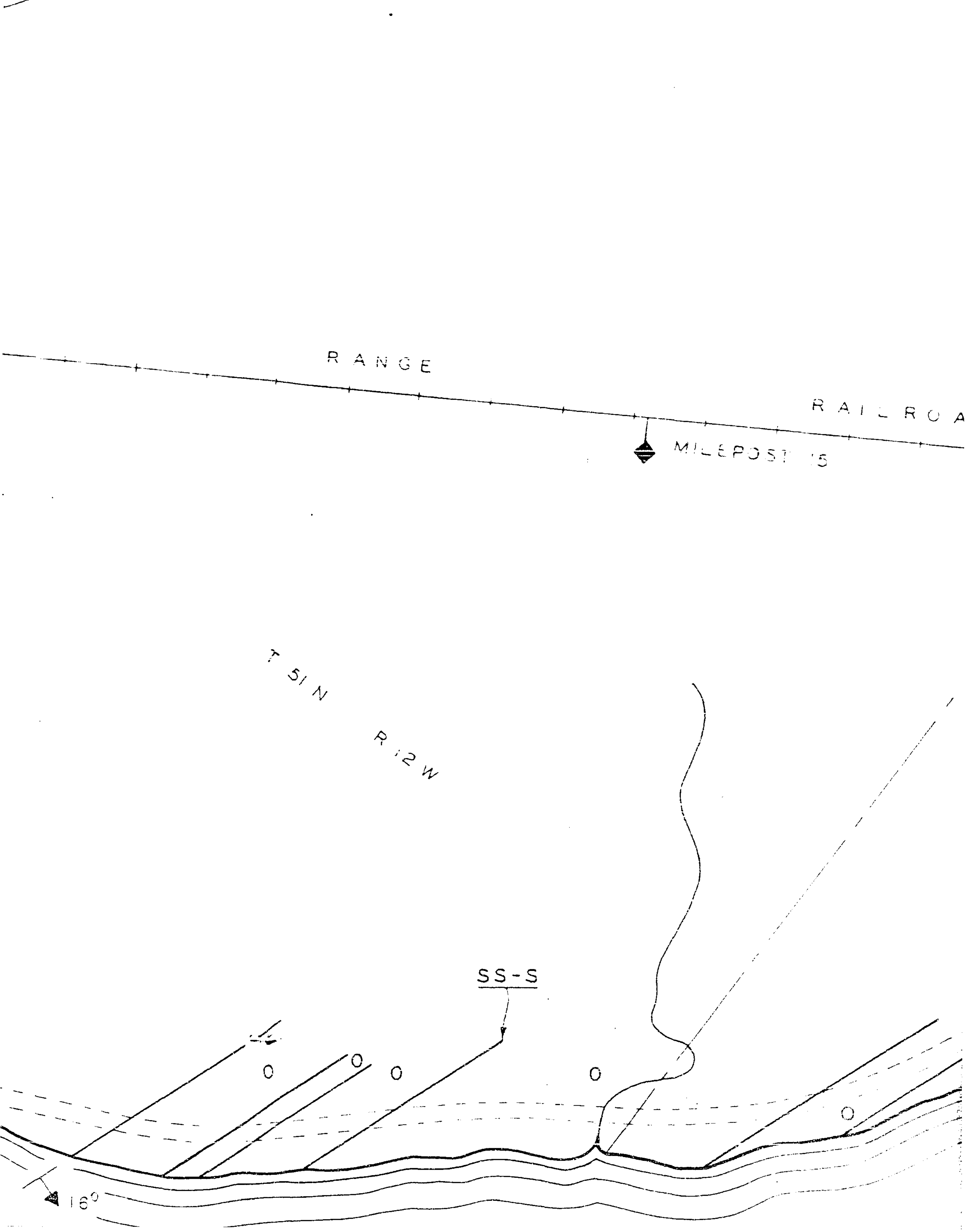
PLATE 7



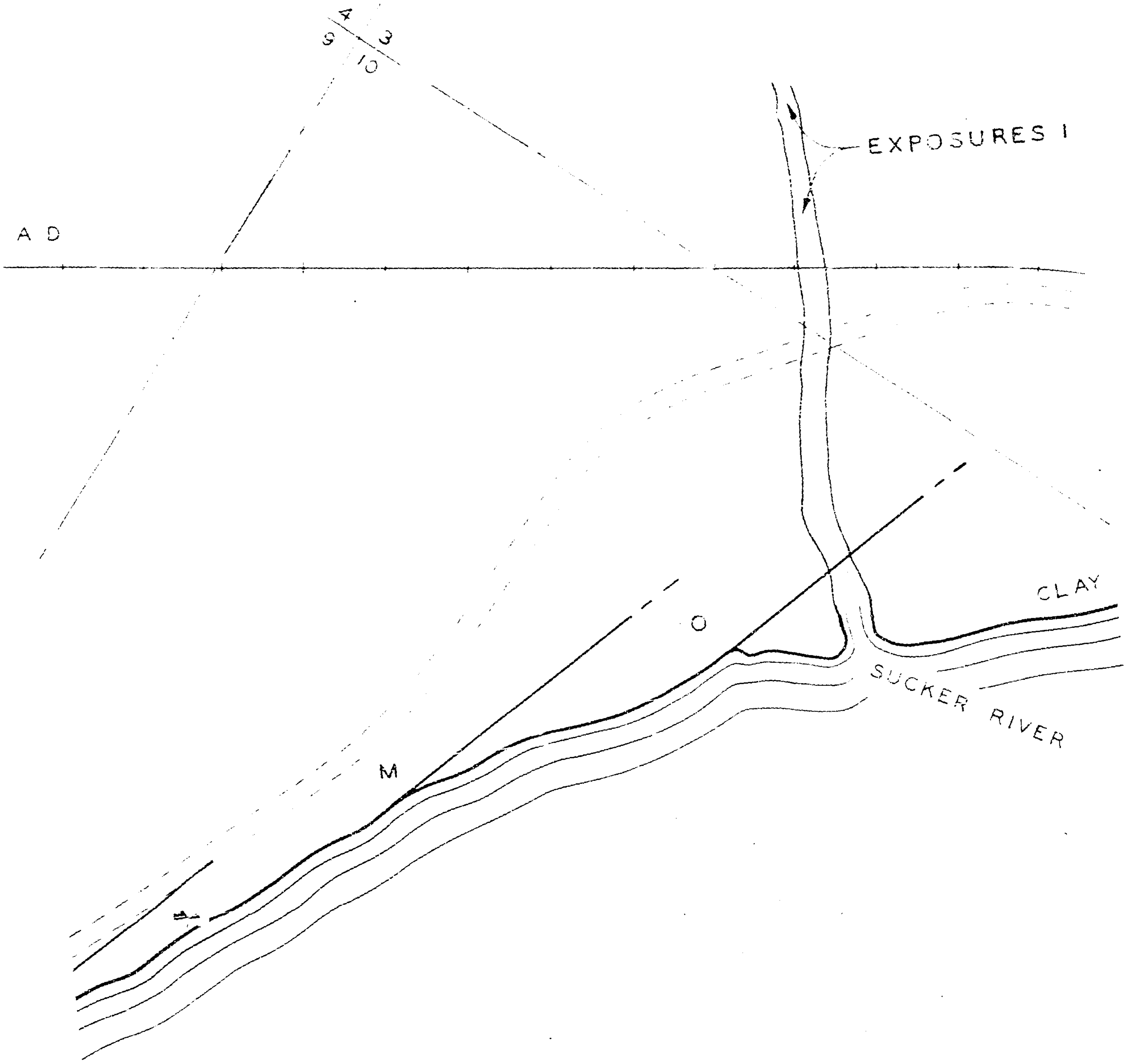
F




IRON
AND
MILE POST
14
8
9
17
16
OPHITE
EXPOSURES
CLAY
BANKS

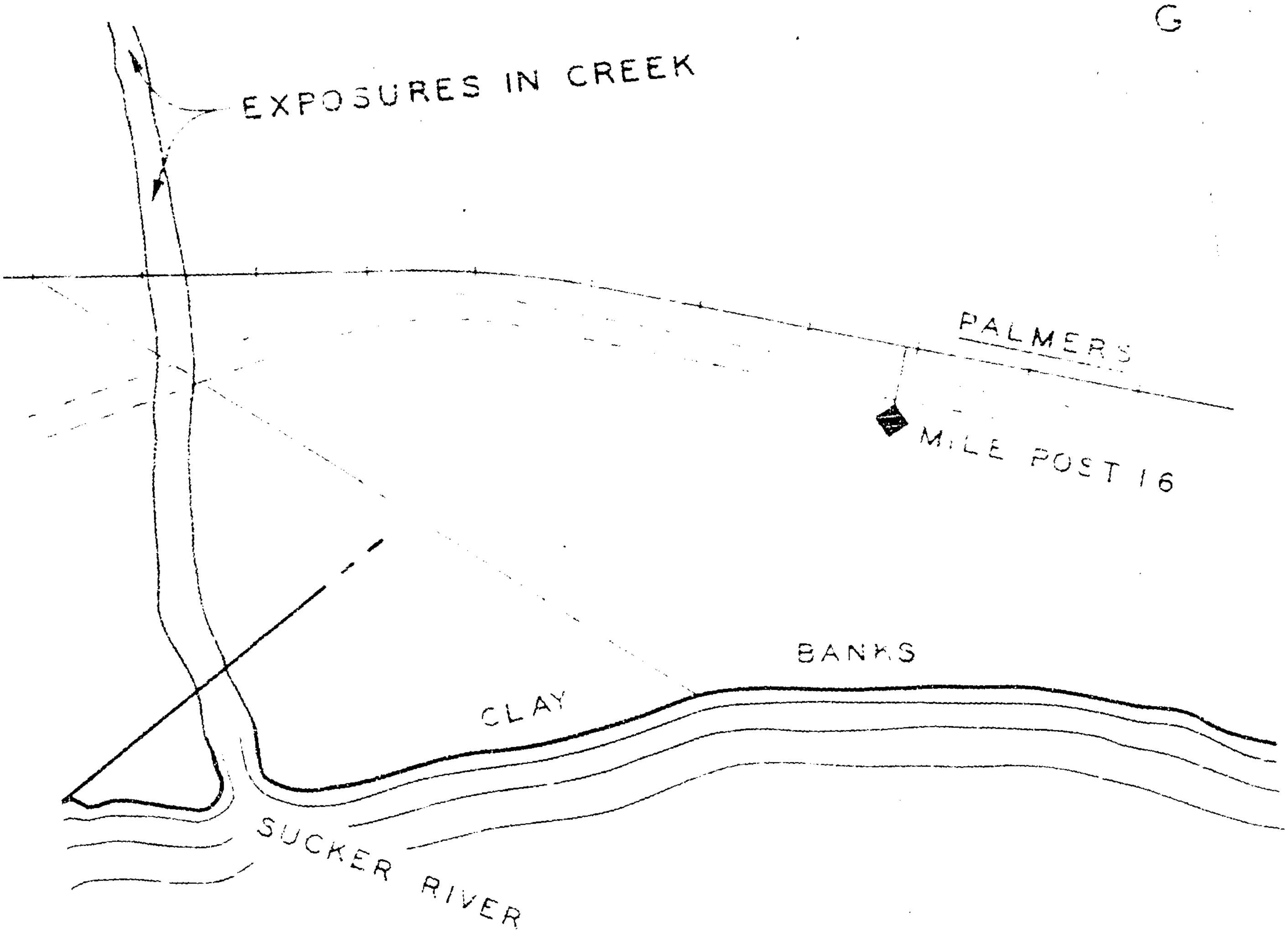


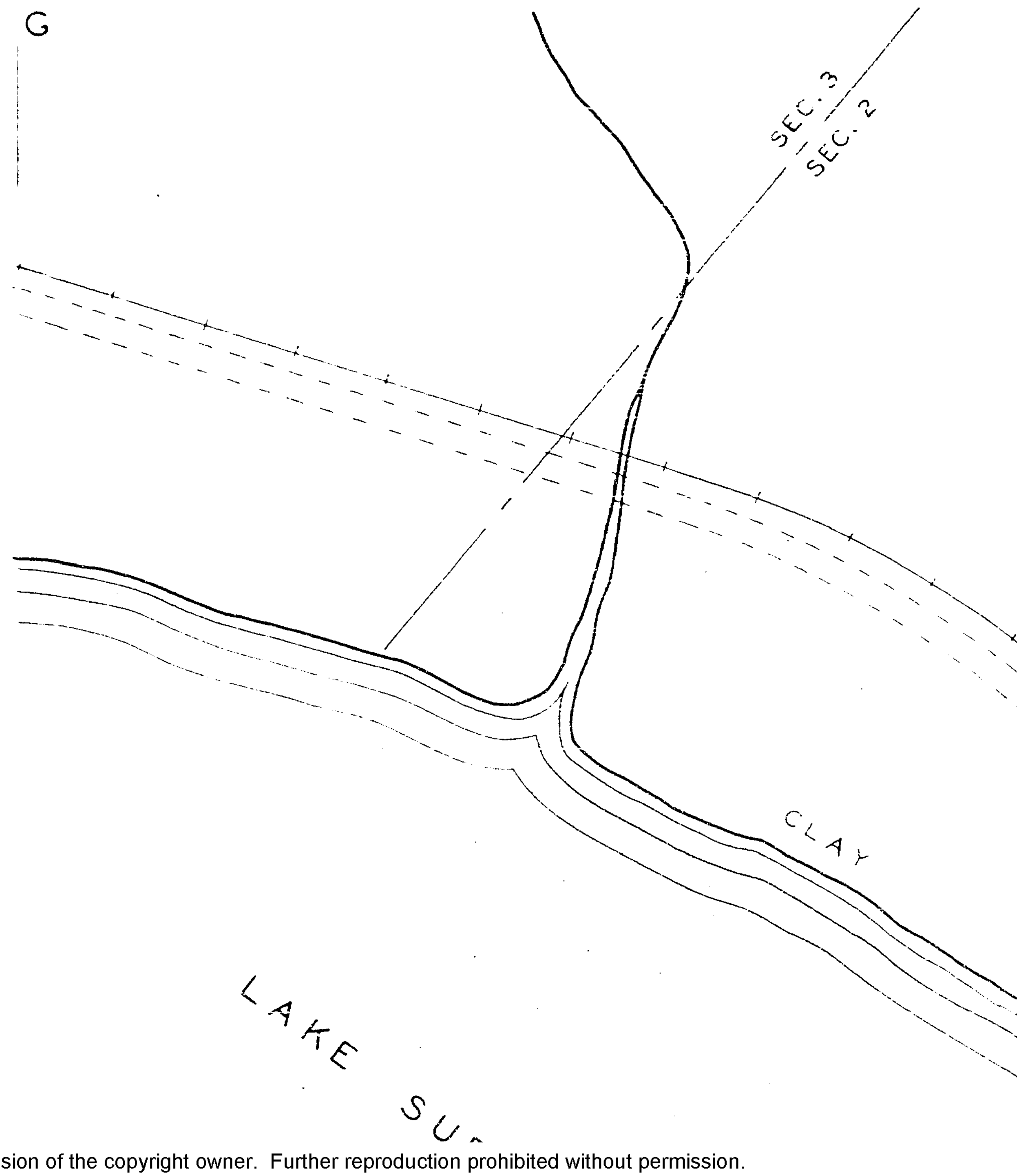
RANGE
RAILROA
MILEPOST 15
T 51 N
R 12 W
SS-S
O
O
O
O
O
16°

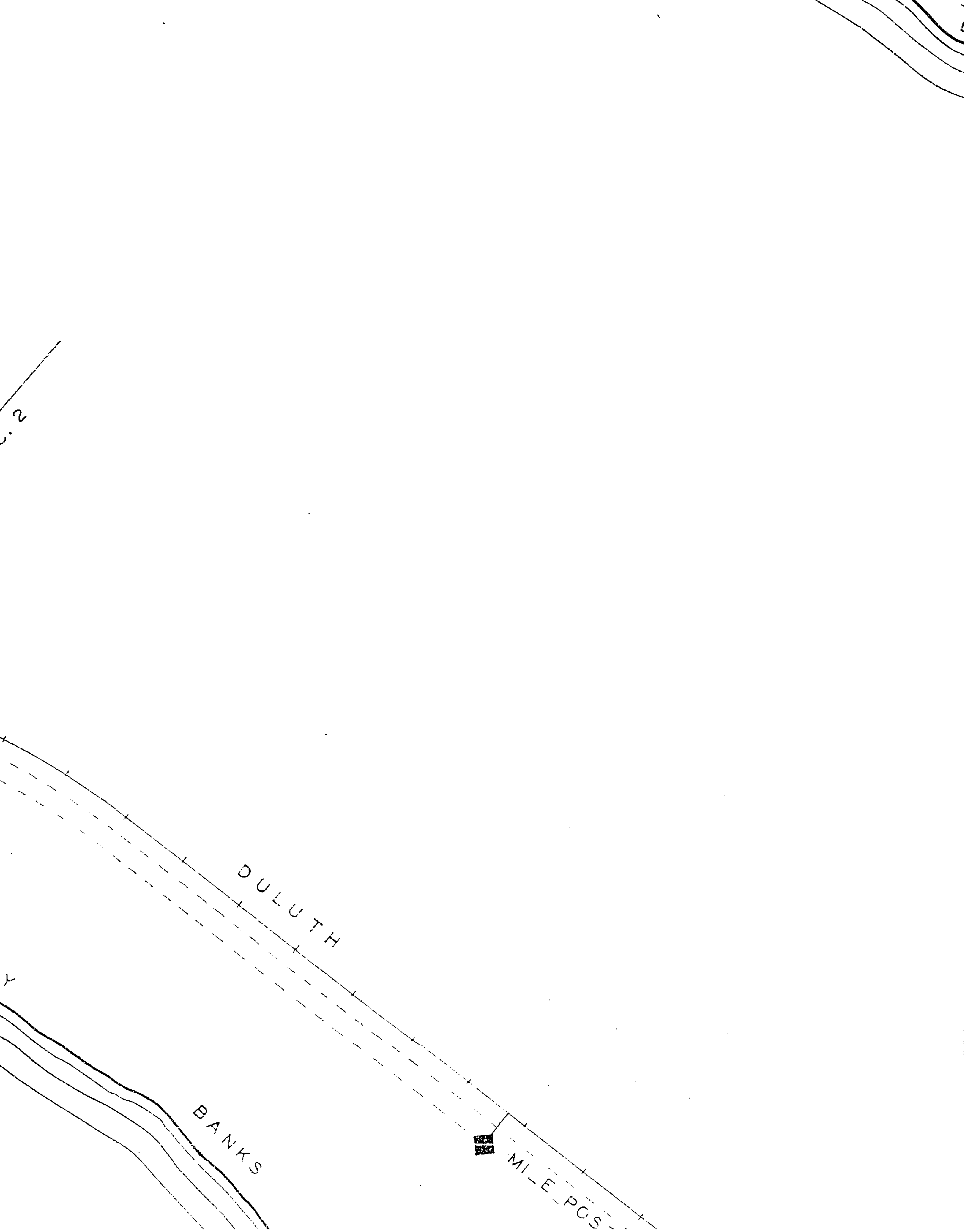


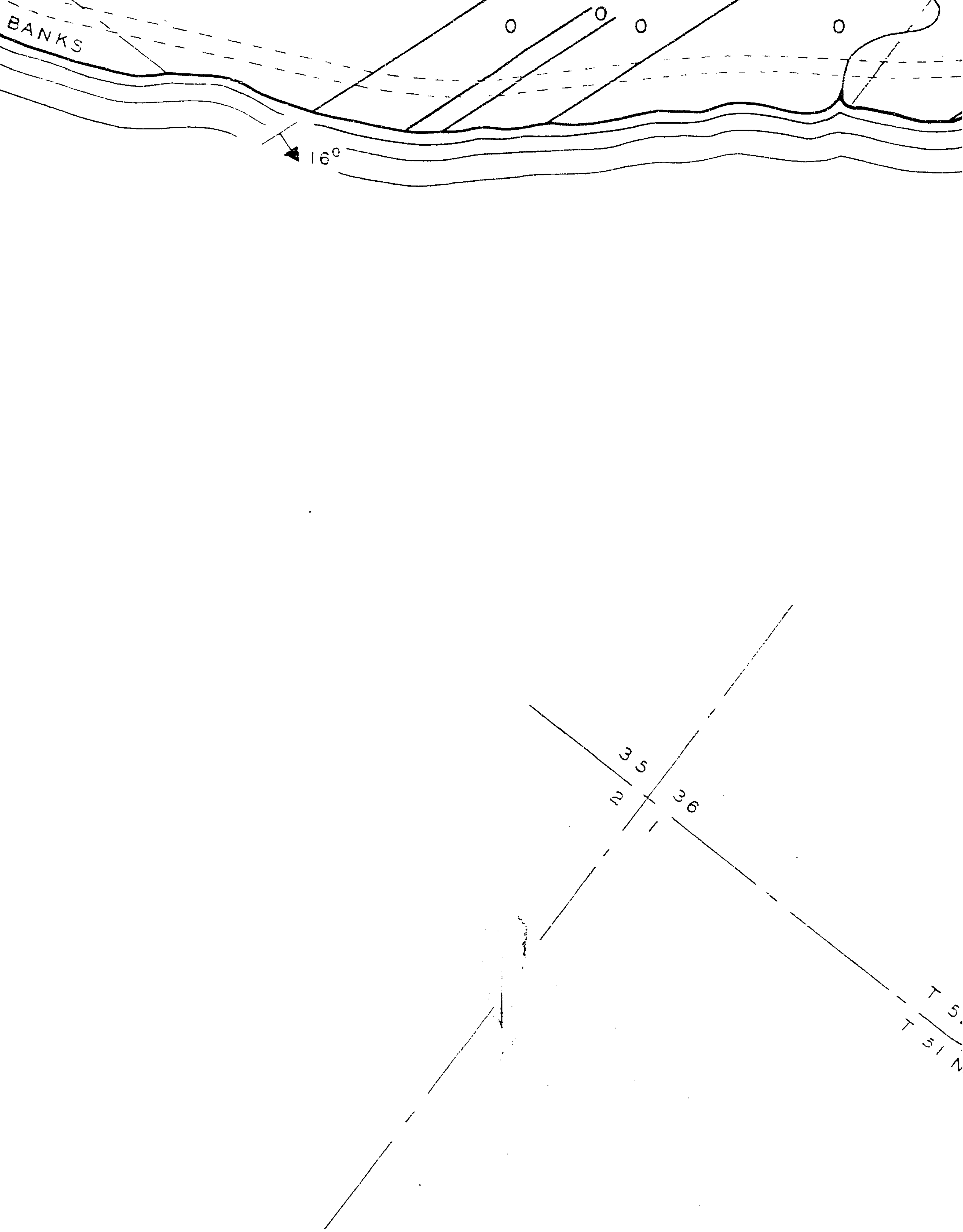
4
3
9
10
EXPOSURES I
A D
CLAY
O
SUCKER RIVER
M

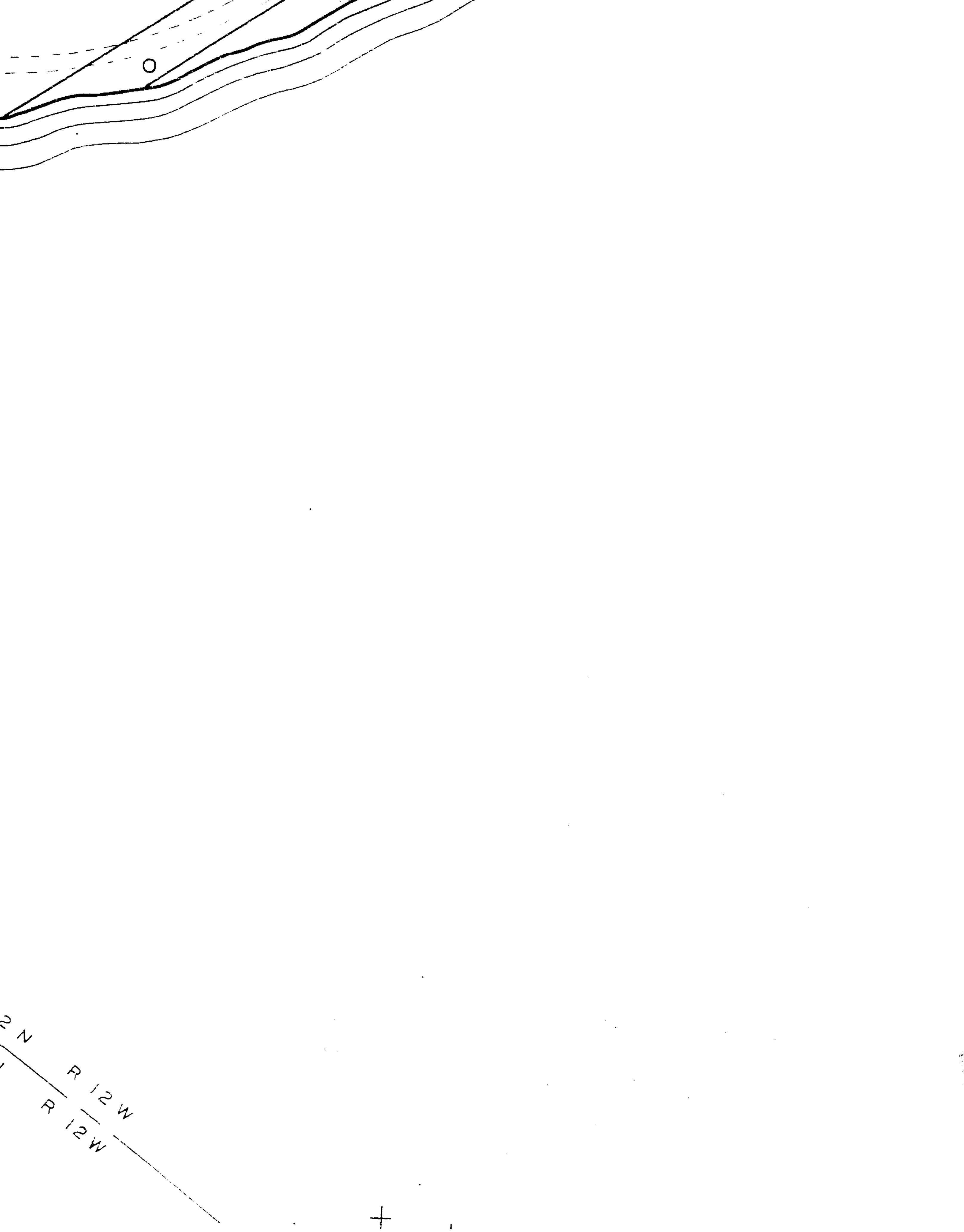
G


EXPOSURES IN CREEK
PALMERS
MILE POST 16
BANKS
CLAY
SUCKER RIVER

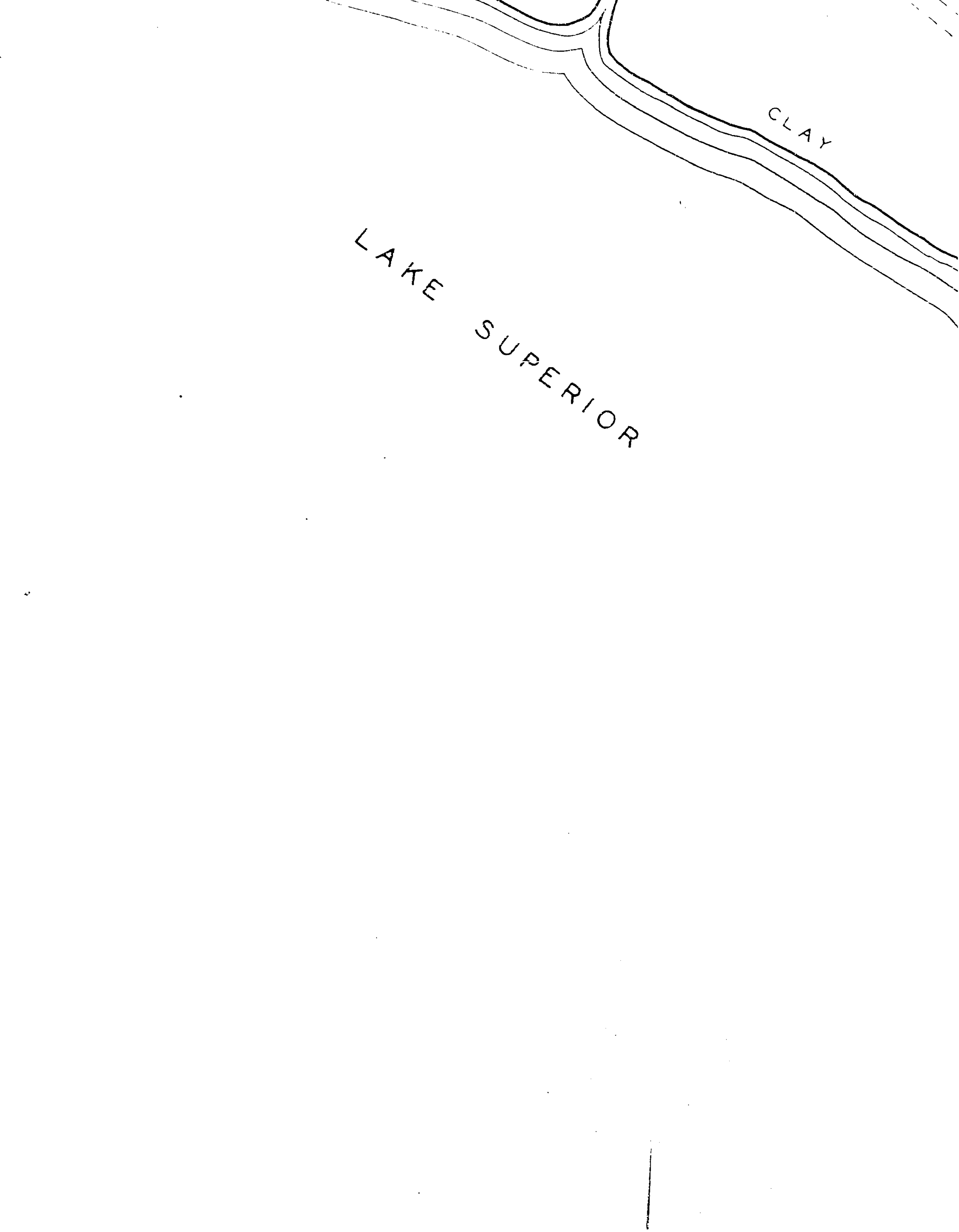

G
SEC. 3
SEC. 2
CLAY
LAKE SU

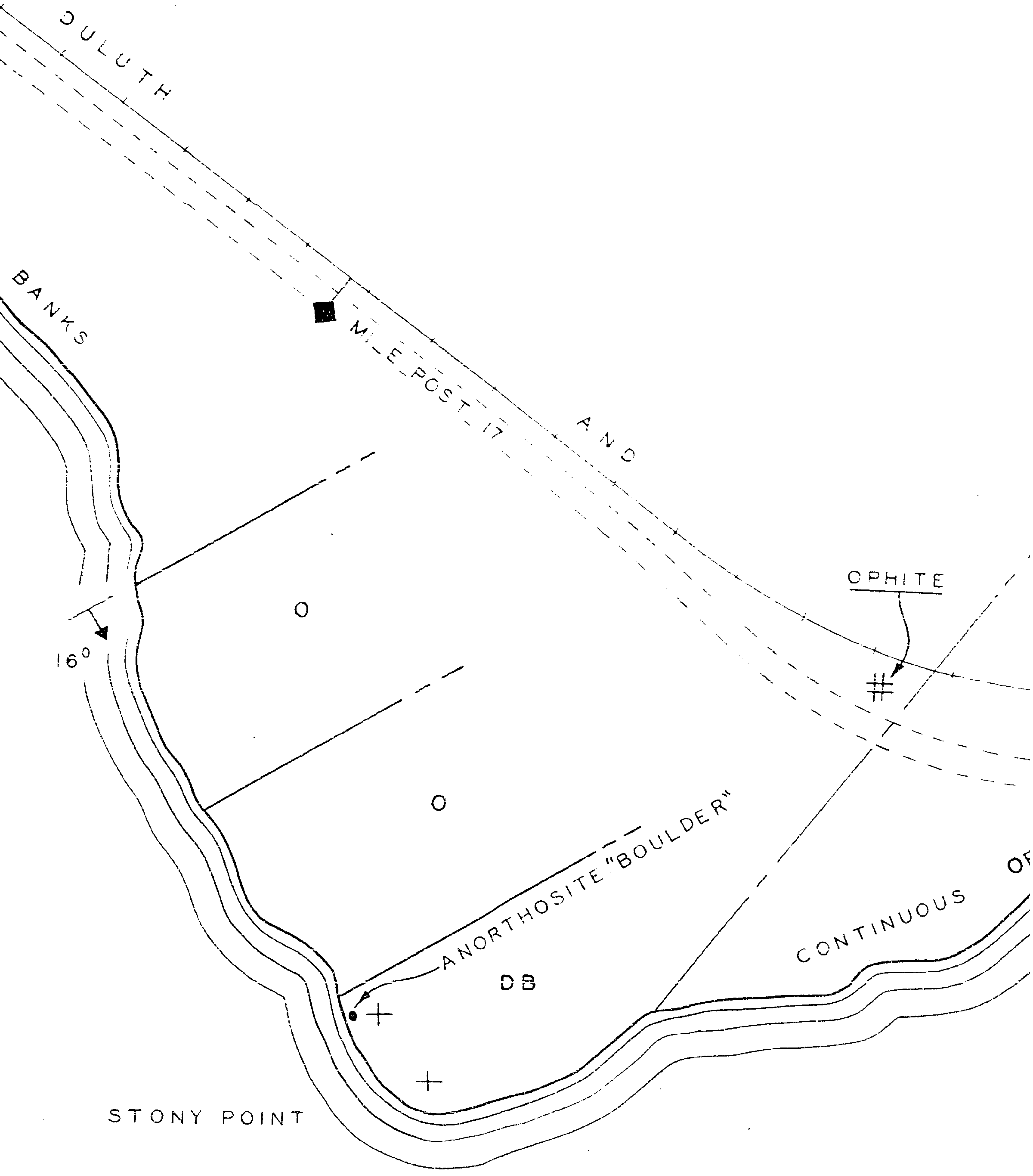

.2
DULUTH
Y
BANKS
MILE POS

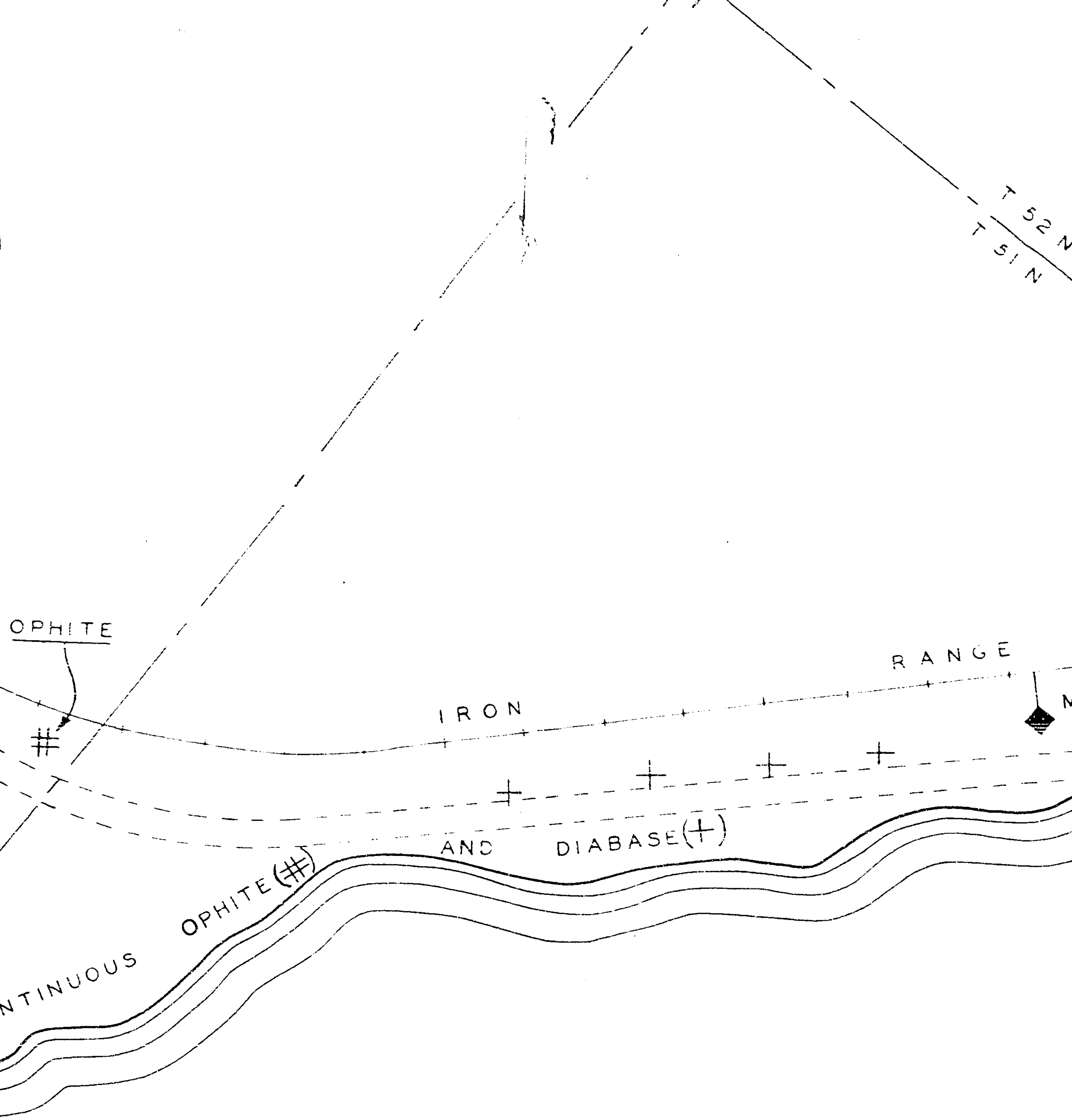

BANKS
0
0
0
0
16°
35
2
36
T 5
T 51 N

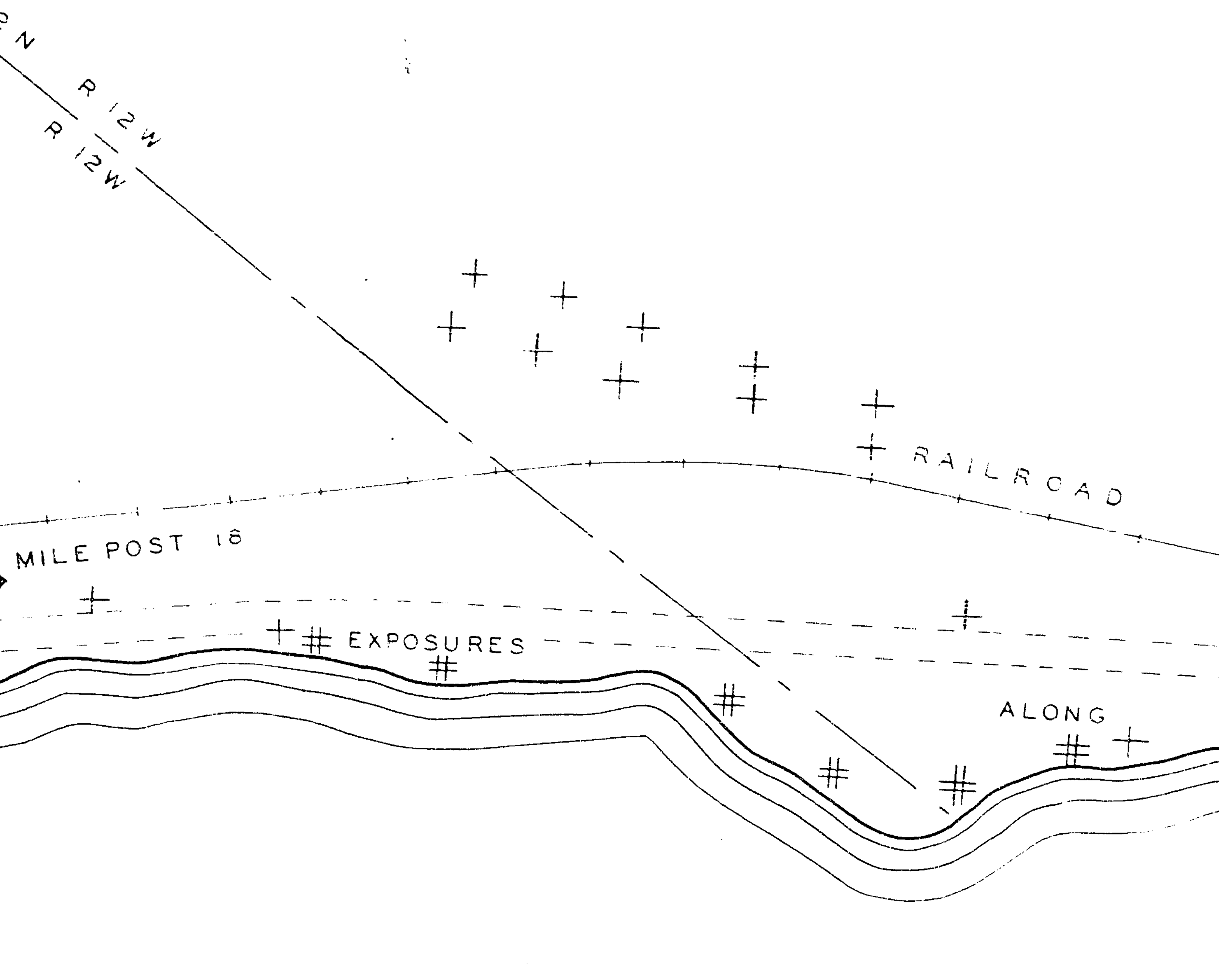

O
2 N
R 12 W
R 12 W

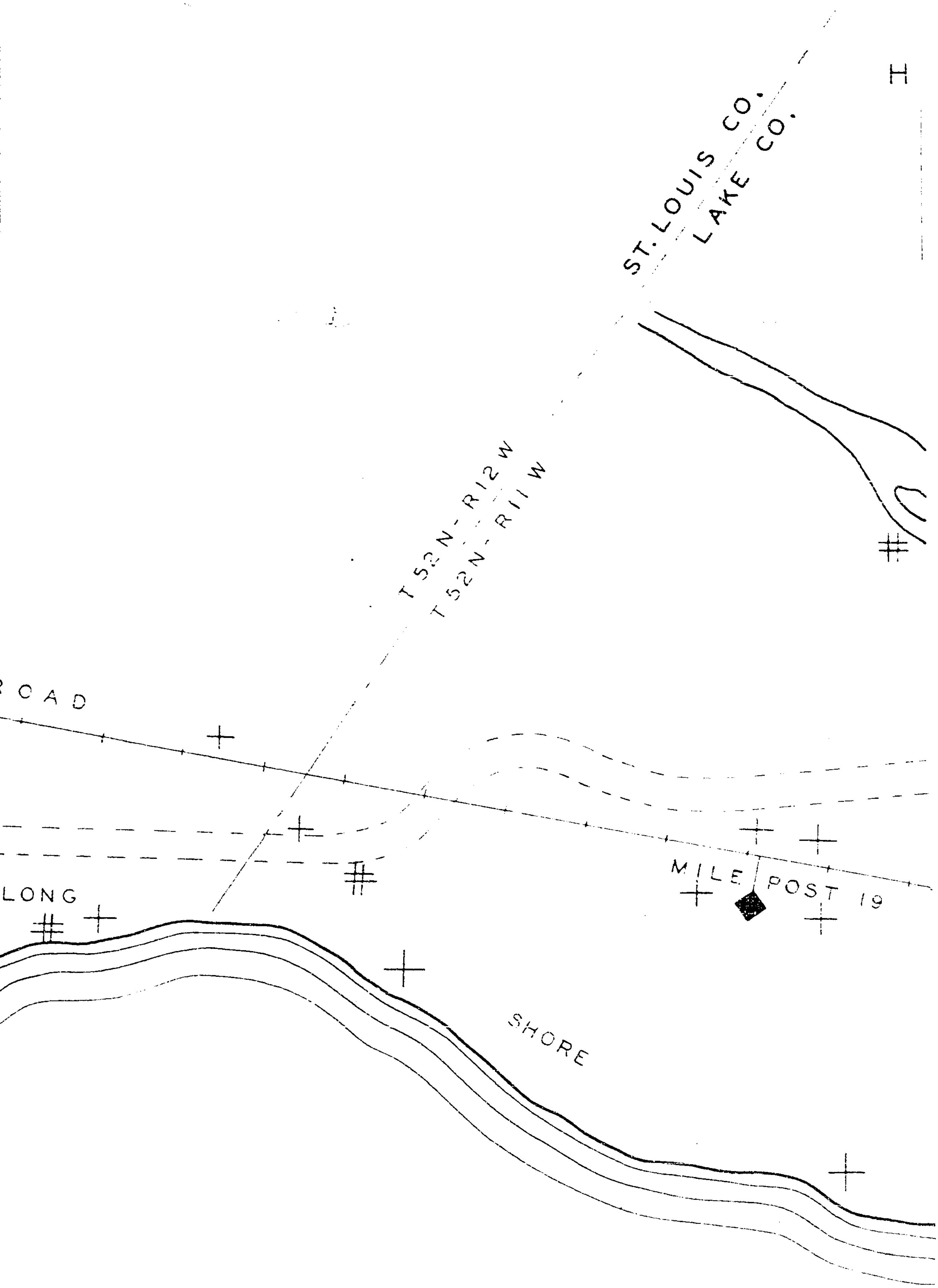

ST. LOUIS CO.
LAKE CO.
N - R.12 W
R 11 W

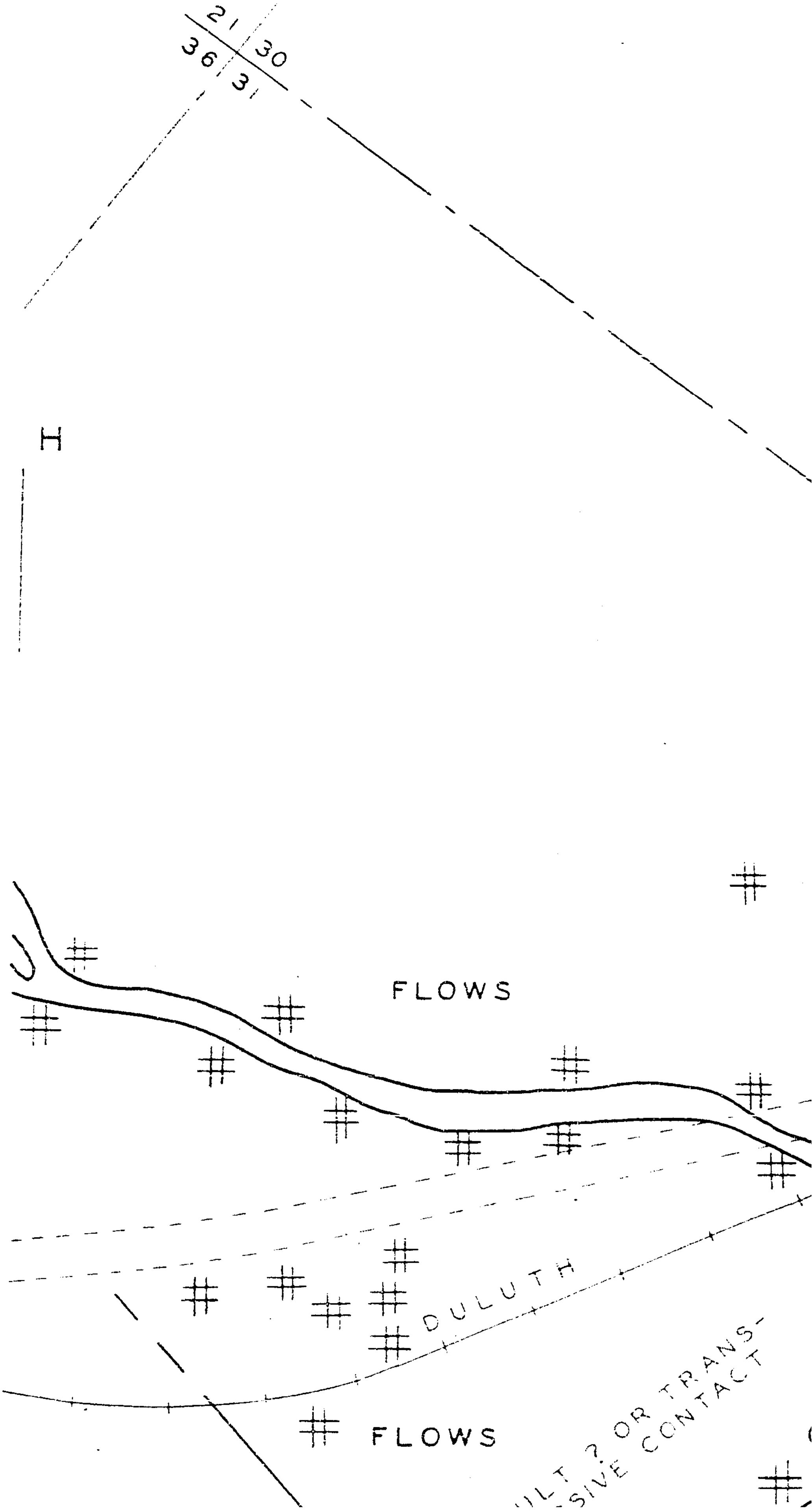

CLAY
LAKE SUPERIOR

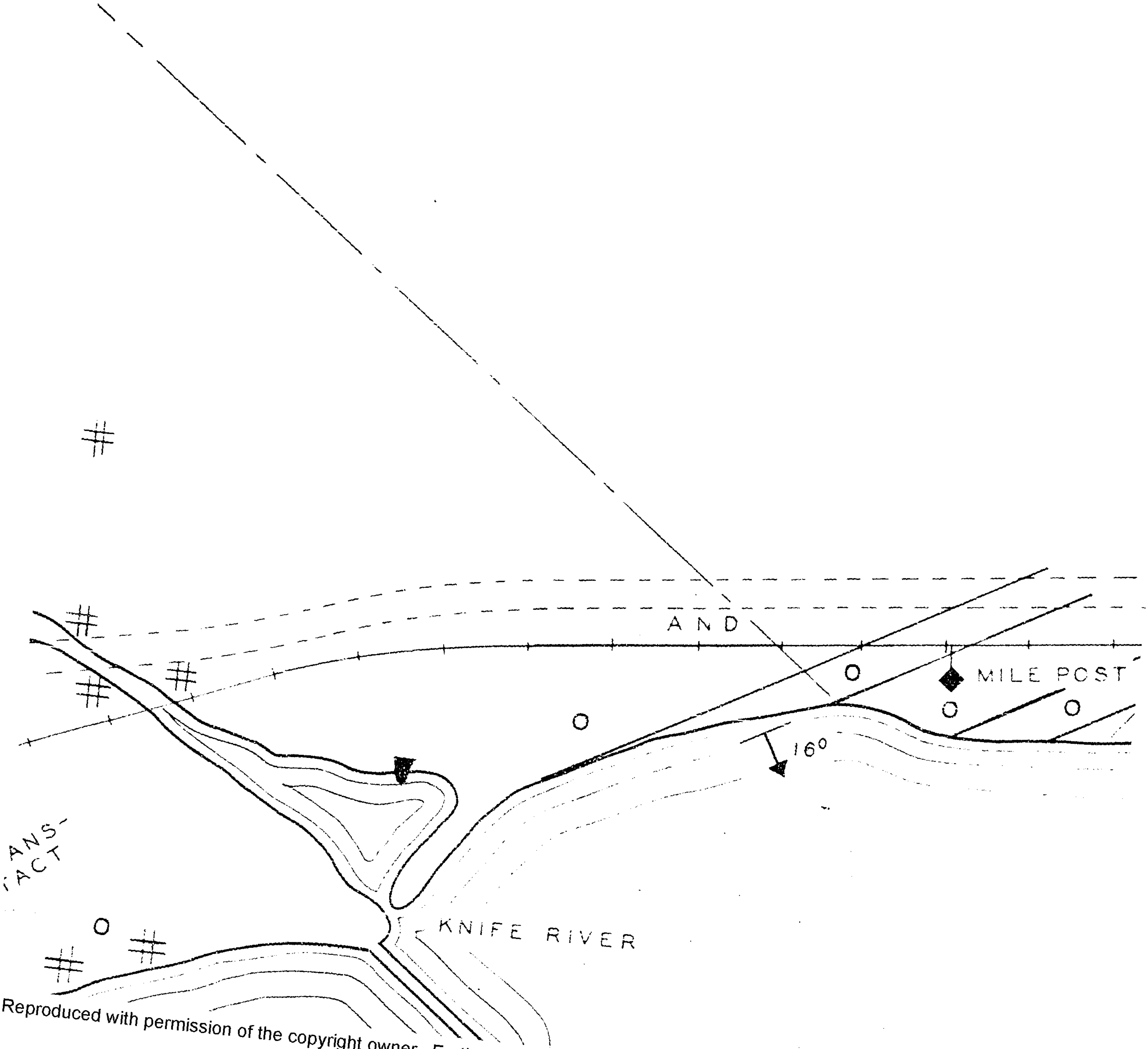

DULUTH
AND
MILE POST 17
BANKS
16°
O
O
OPHITE
ANORTHOSITE "BOULDER"
DB
CONTINUOUS
OF
STONY POINT

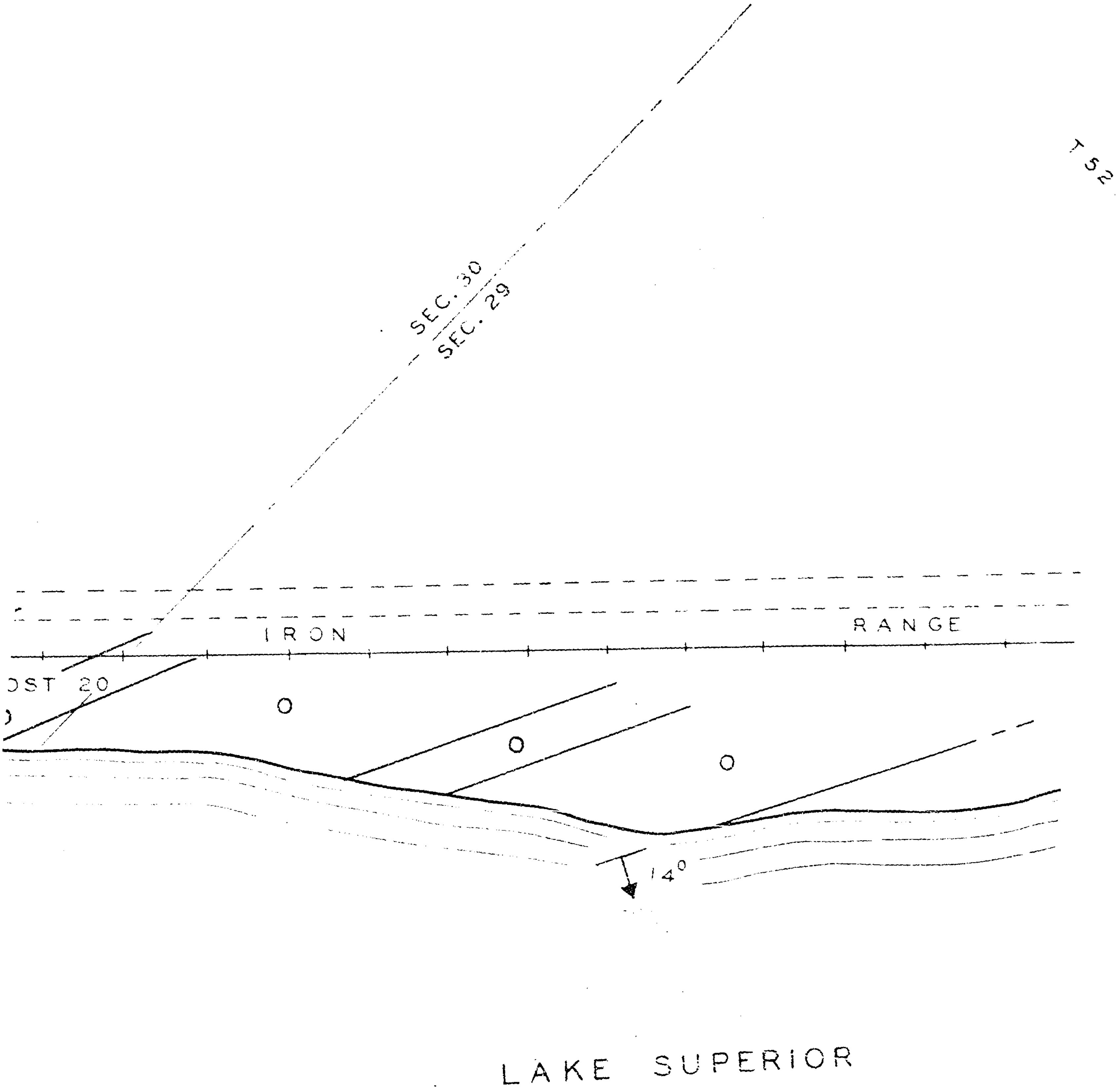

T 52 N
T 51 N
OPHITE
IRON
RANGE
AND
DIABASE
OPHITE
NTINUOUS


N
R 12 W
R 12 W
RAILROAD
MILE POST 18
EXPOSURES
ALONG


H
ST. LOUIS CO.
LAKE CO.
T52N-R12W
T52N-R11W
ROAD
LONG
MILE POST 19
SHORE


21
30
36
31
H
FLOWS
DULUTH
FLOWS
ULT ? OR TRANS-
SIVE CONTACT


AND
MILE POST
16°
ANS-
ACT
KNIFE RIVER


SEC. 30
SEC. 29
T 52
IRON
RANGE
OST 20
O
O
O
14°
LAKE SUPERIOR

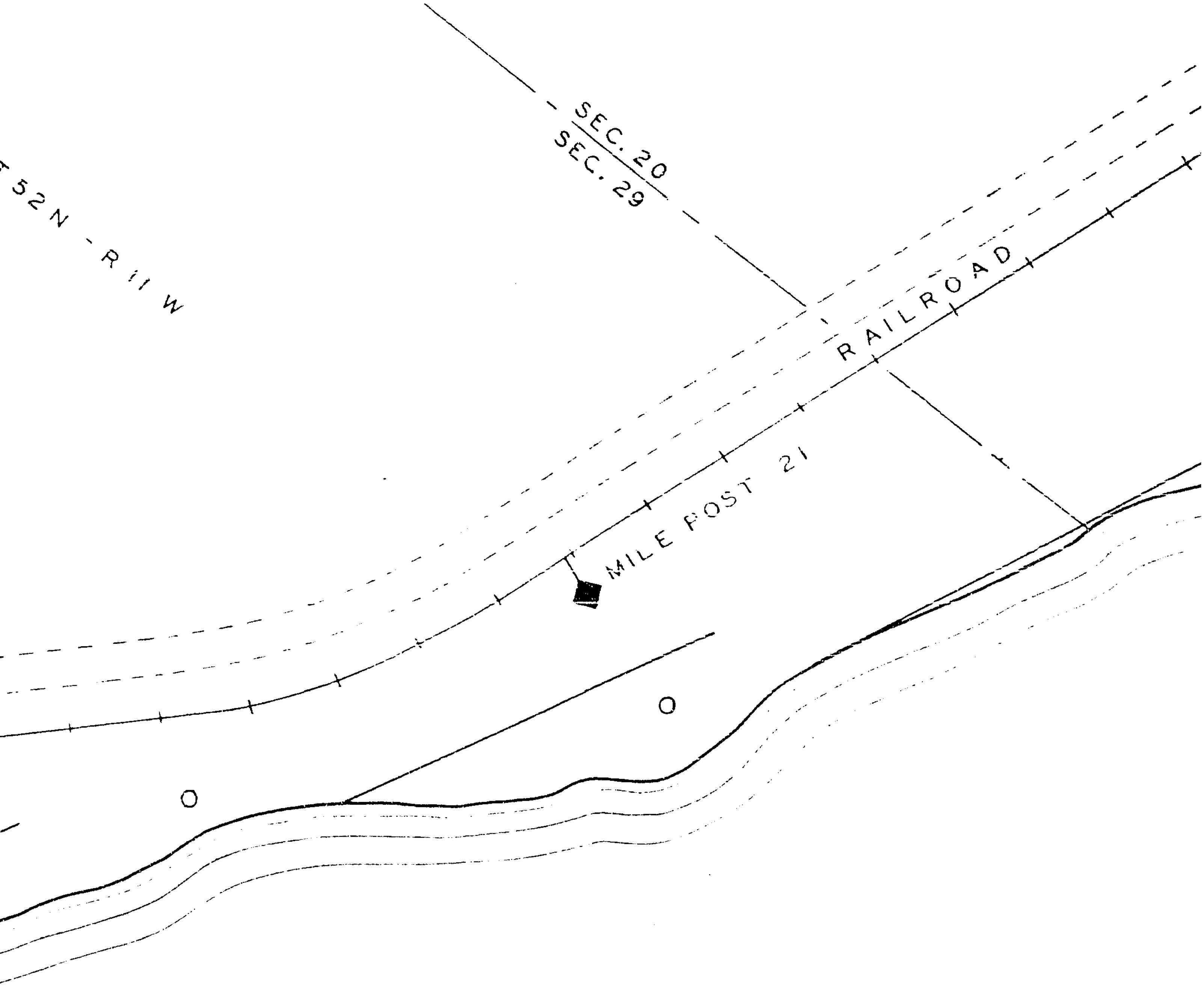
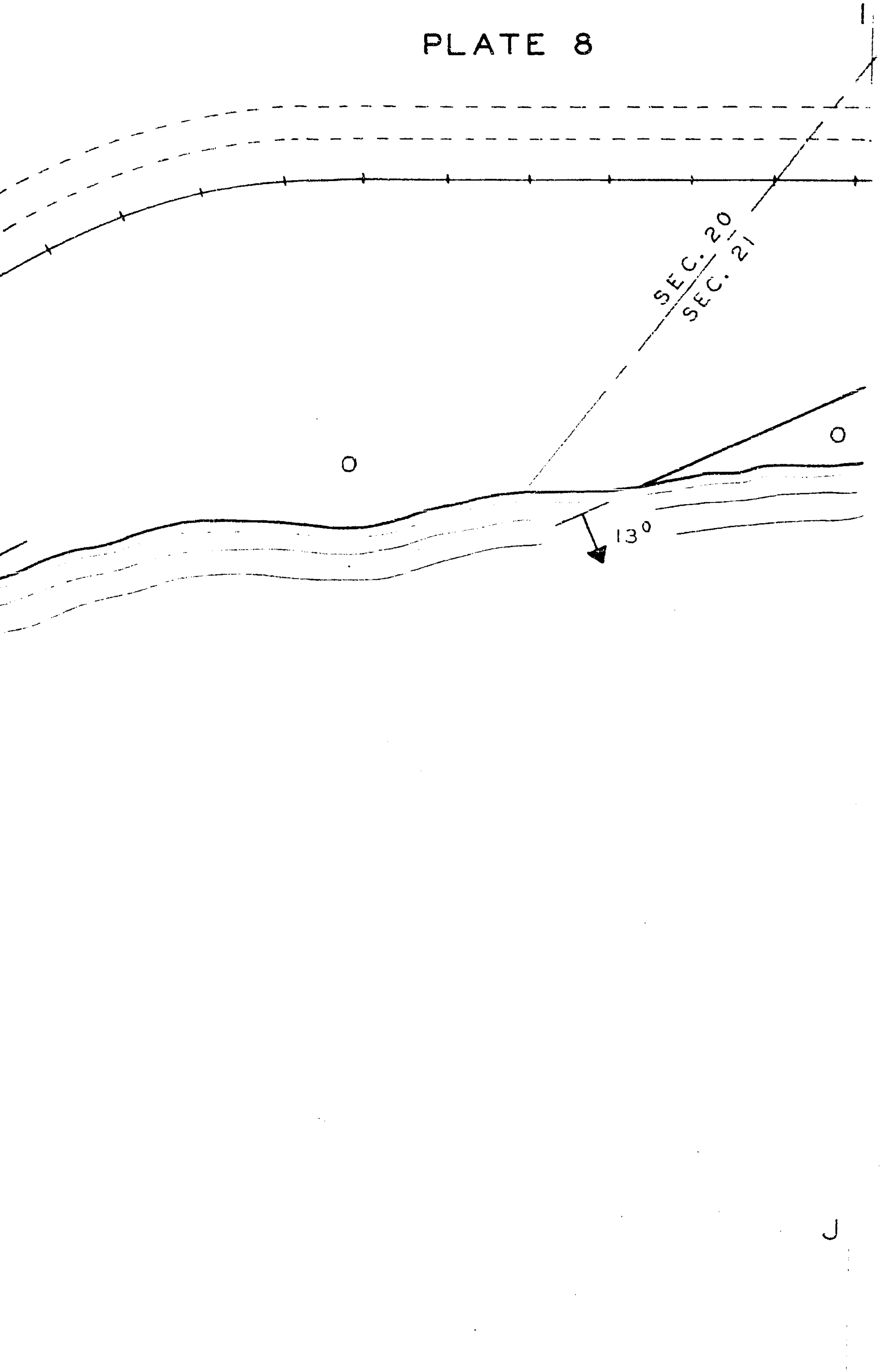
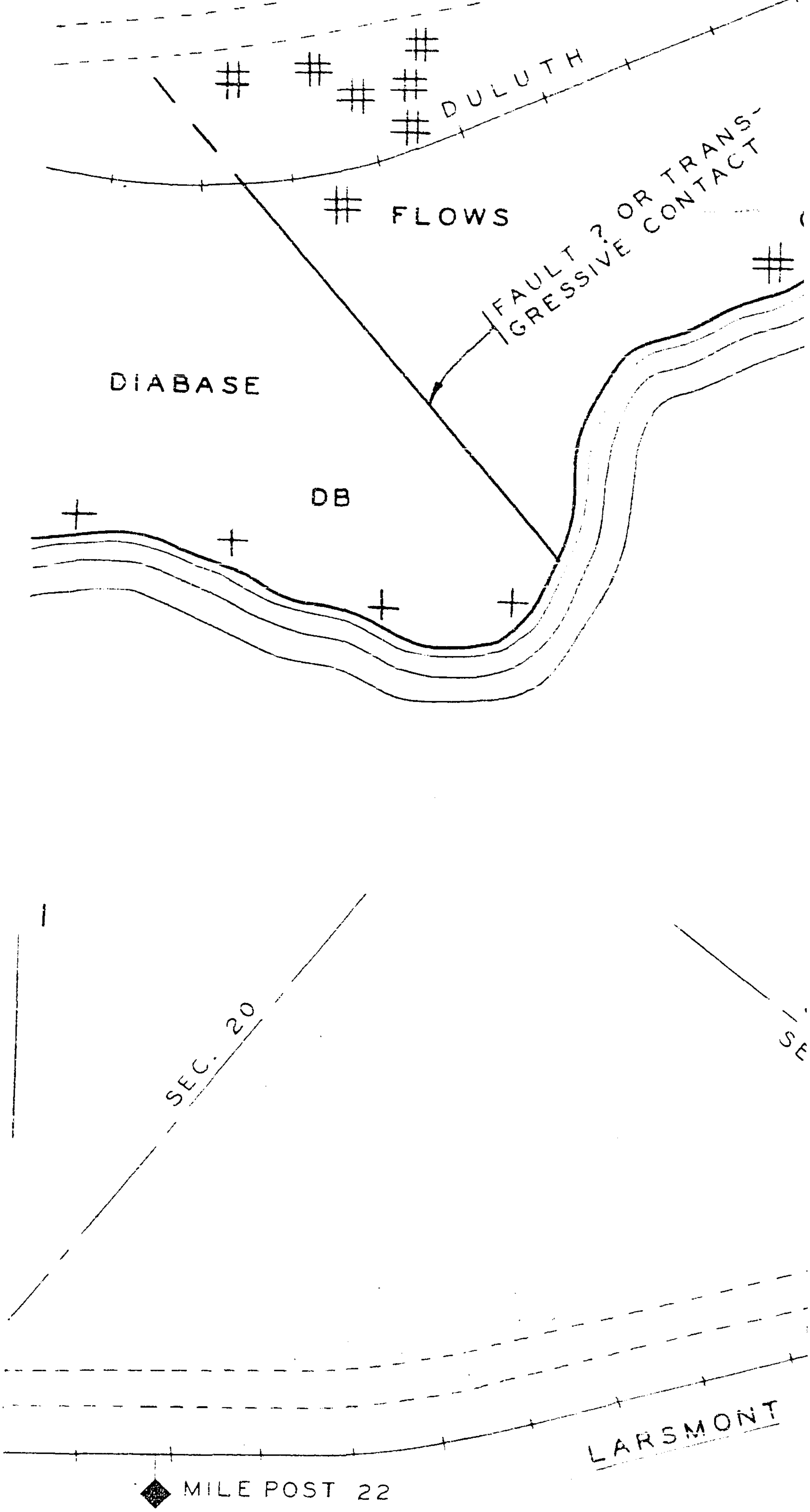
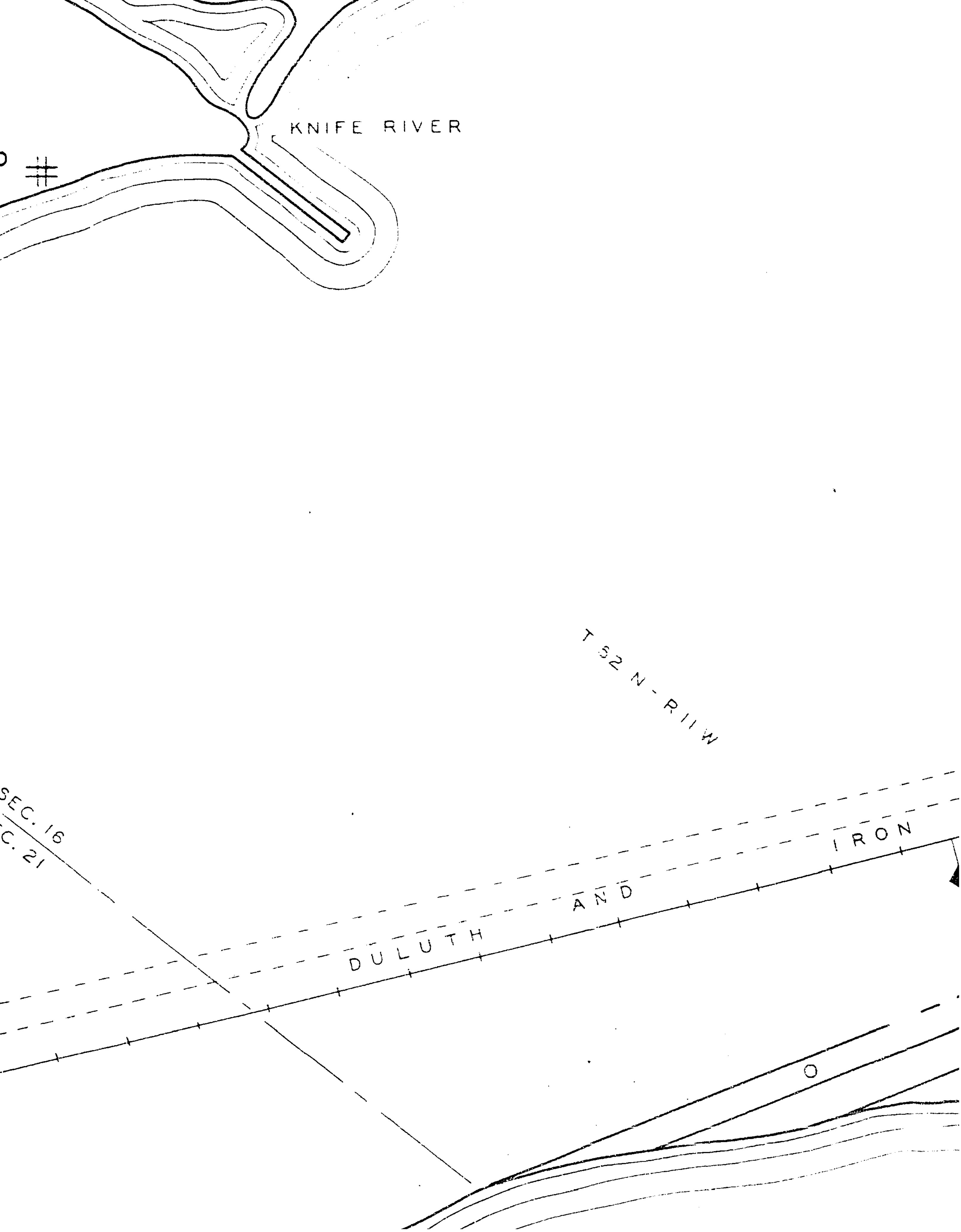
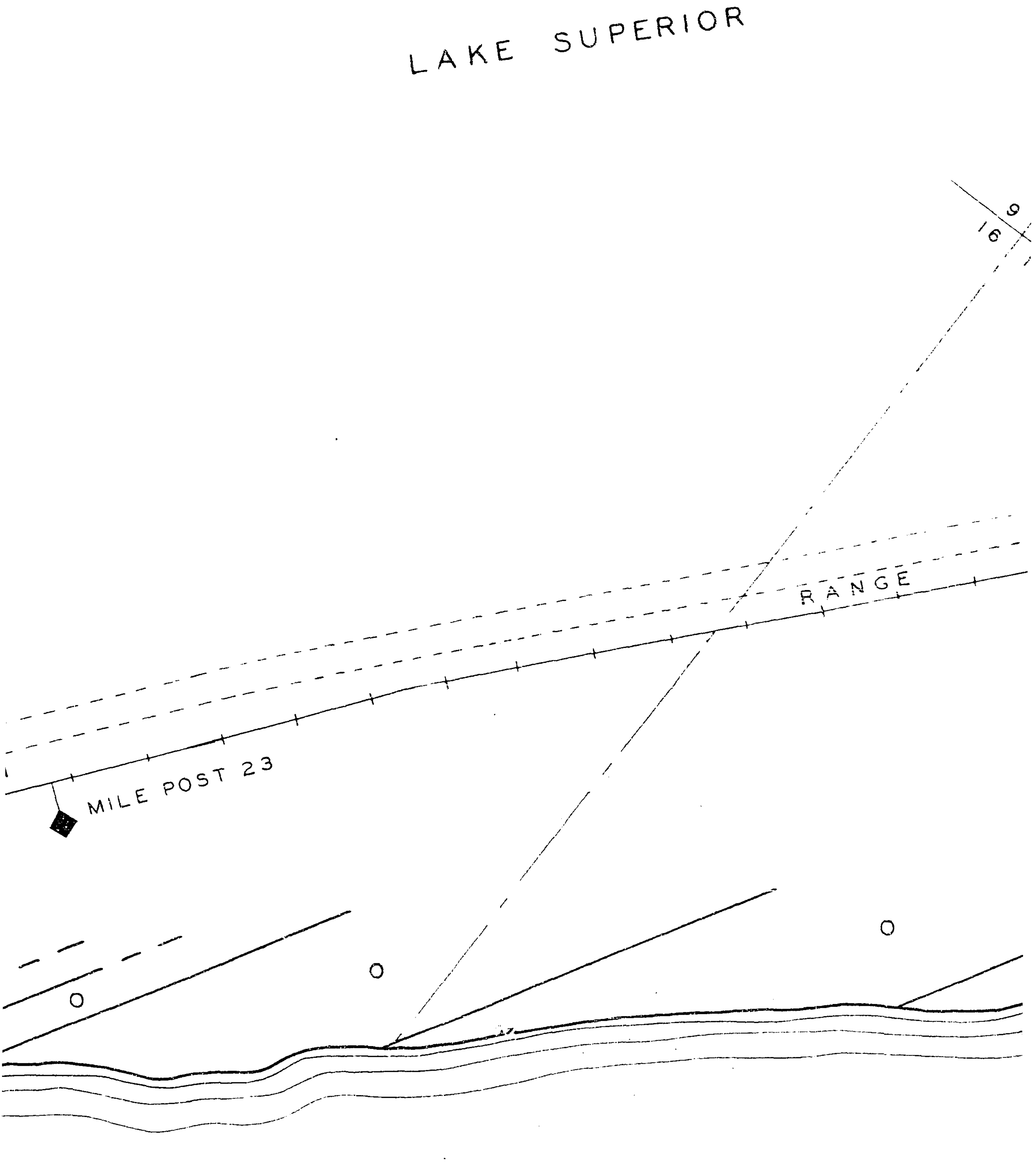

52N - R 11 W
SEC. 20
SEC. 29
RAILROAD
MILE POST 21

PLATE 8

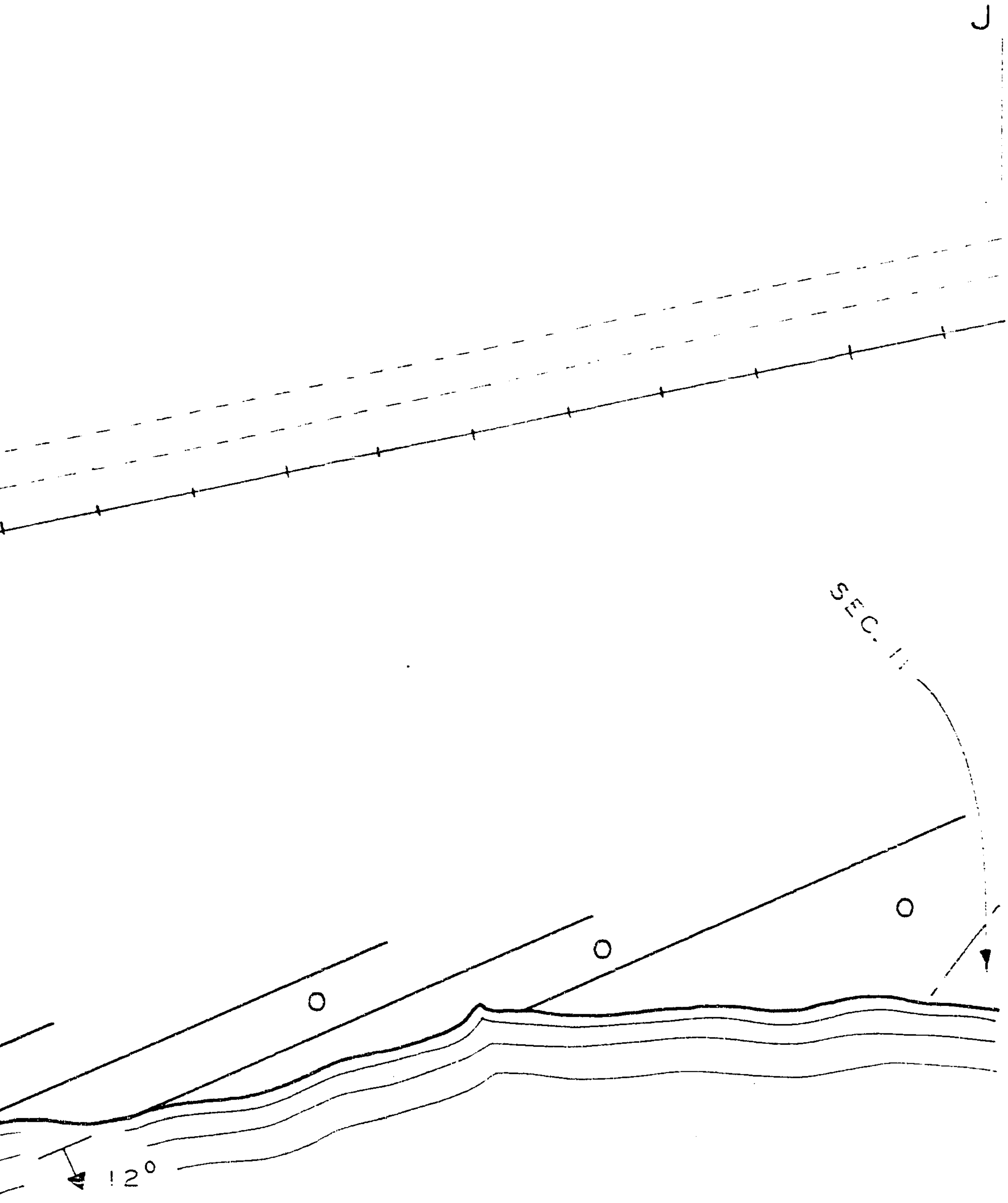


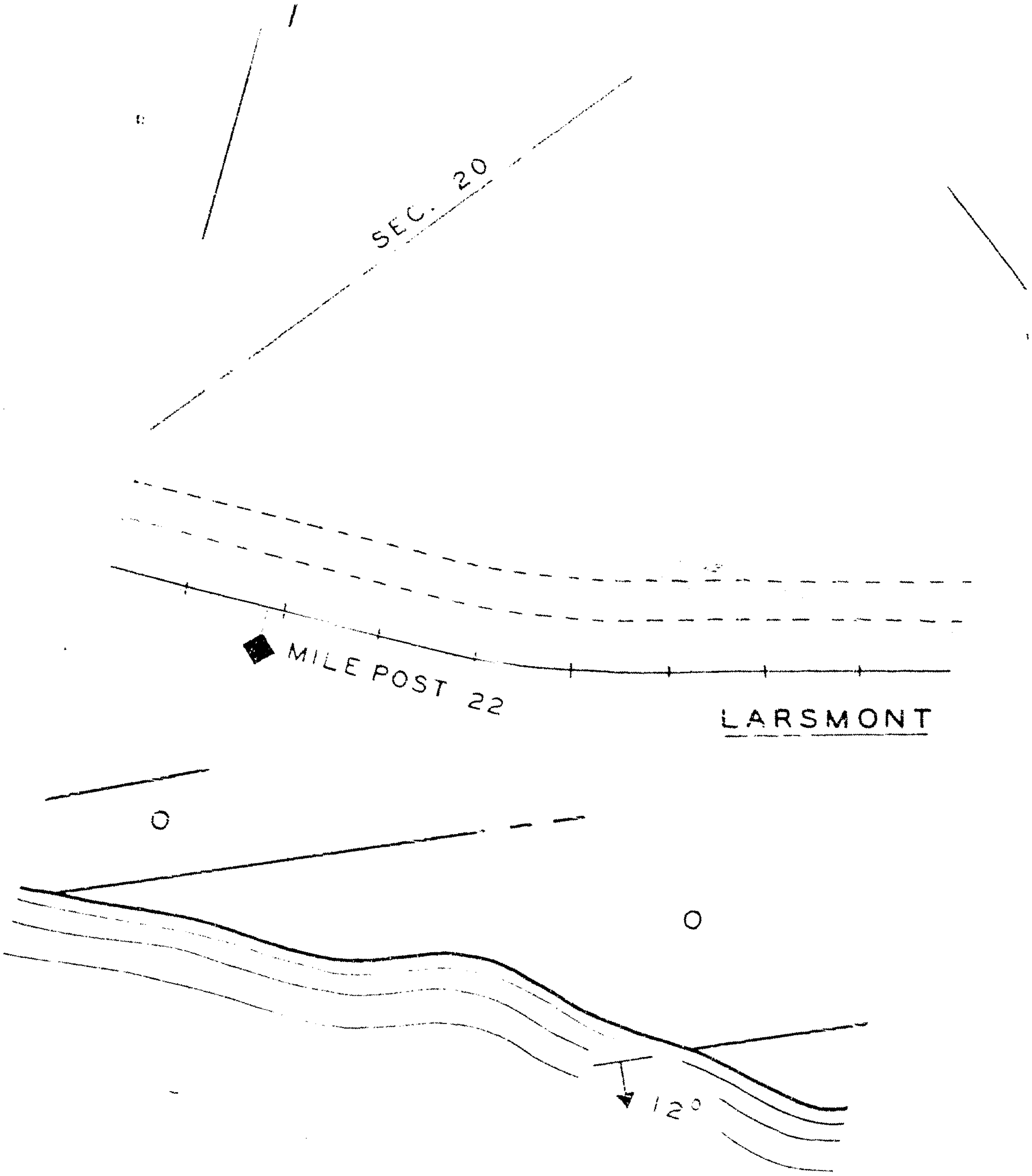

DULUTH
FLOWS
FAULT ? OR TRANSGRESSIVE CONTACT
DIABASE
DB
SEC. 20
LARSMONT
MILE POST 22

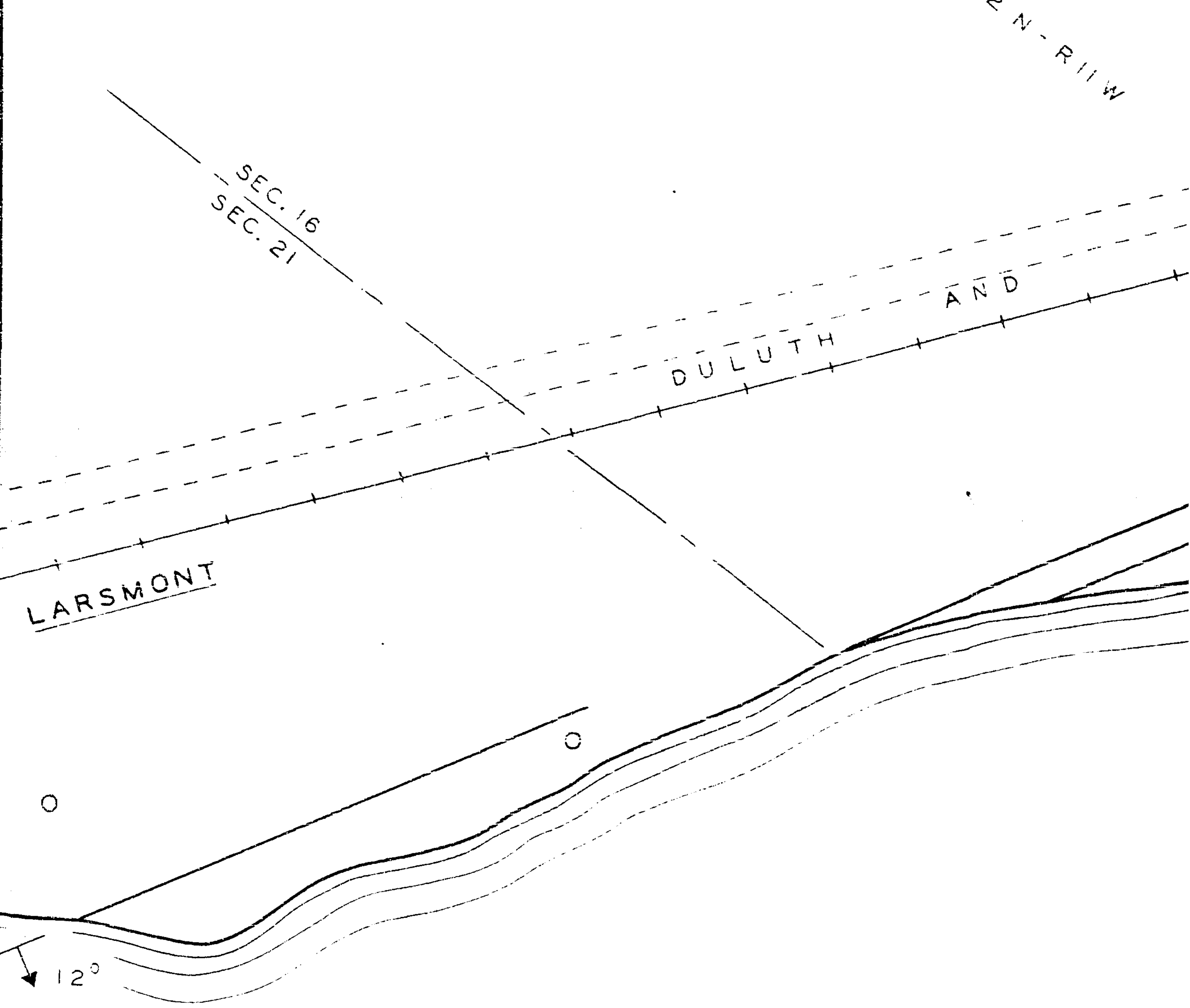

KNIFE RIVER
T 52 N - R 11 W
SEC. 16
C. 21
DULUTH AND IRON
O

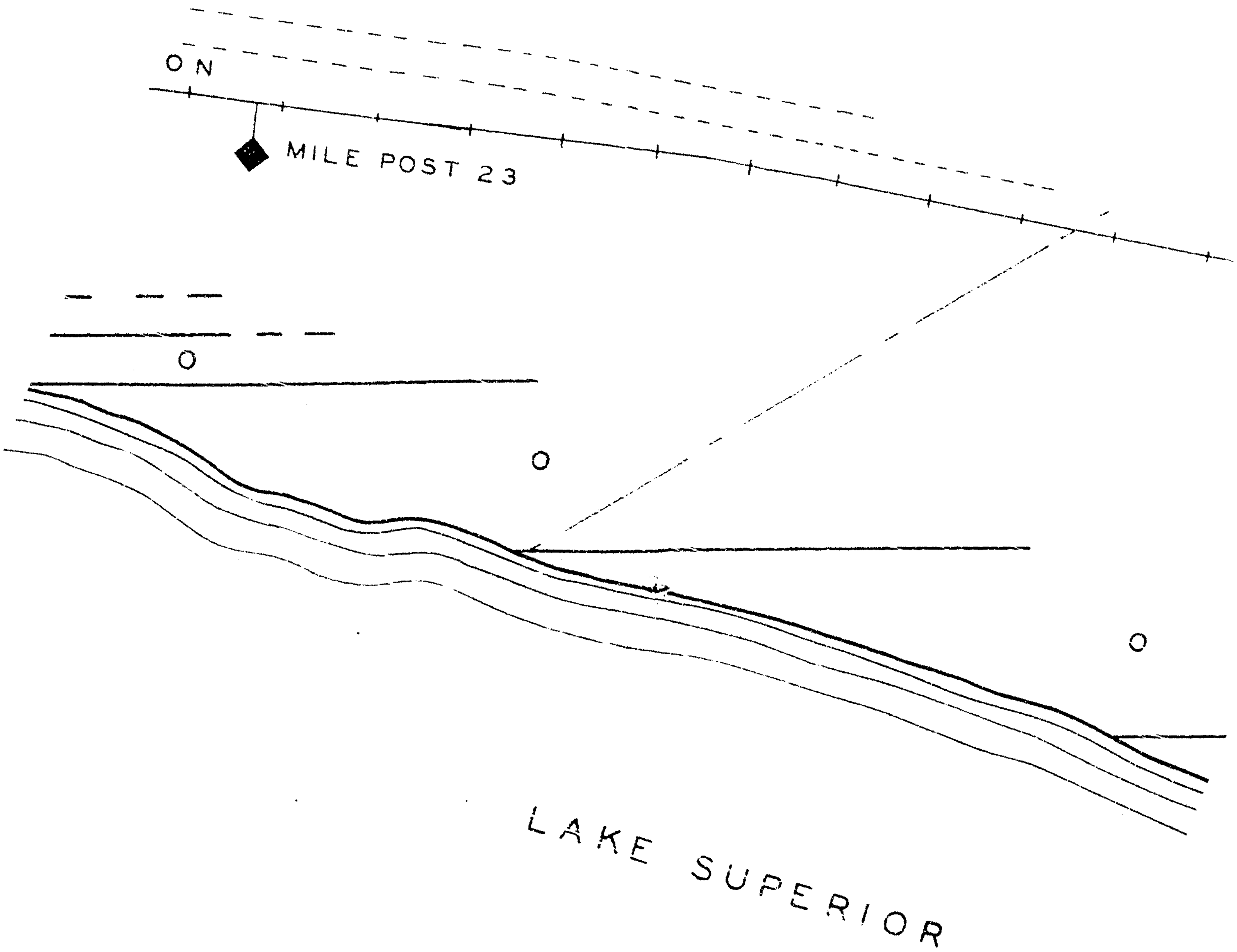

LAKE SUPERIOR
9
16
RANGE
MILE POST 23
O
O
O

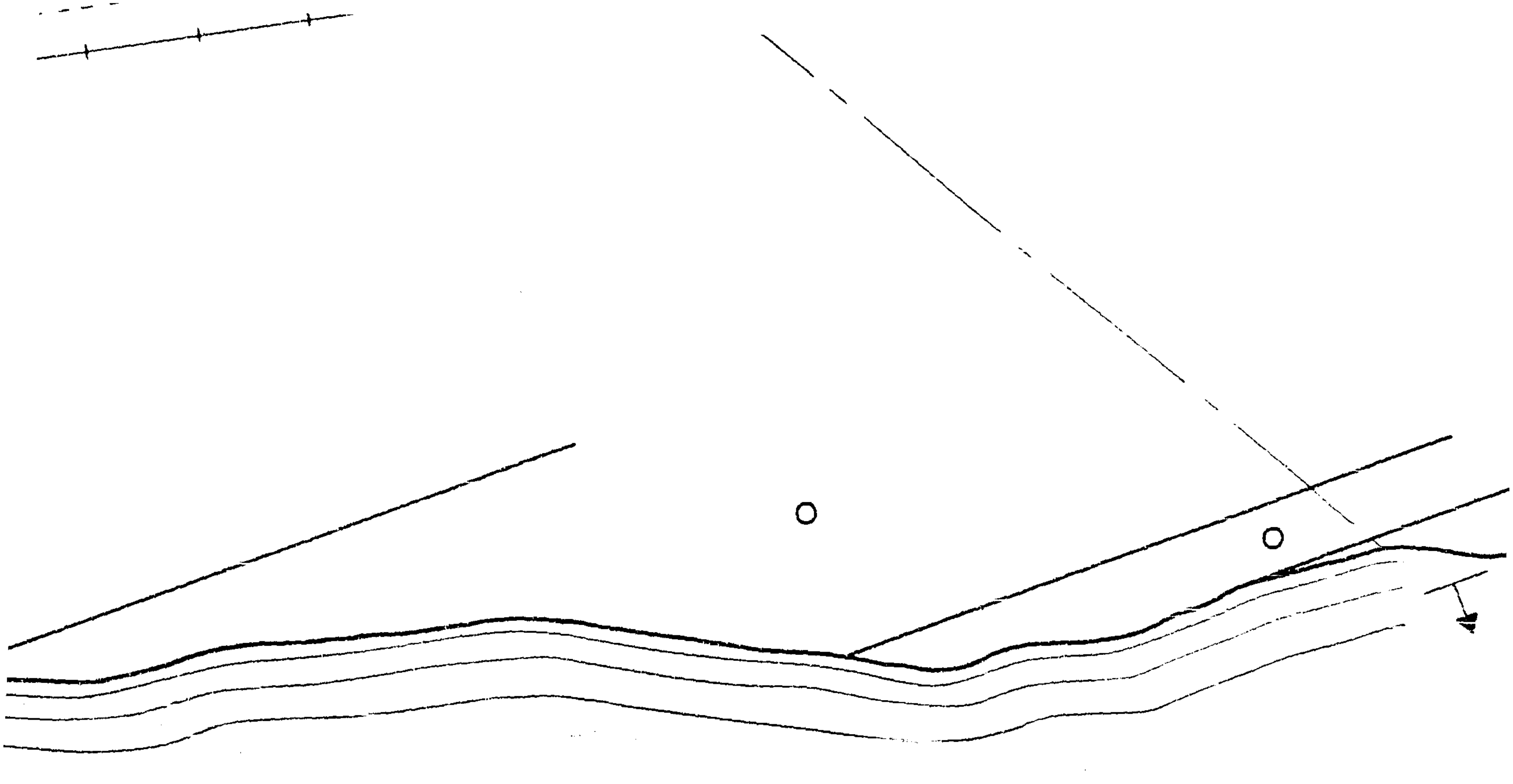

9
10
16
15
RAILROAD
MILE POST 24

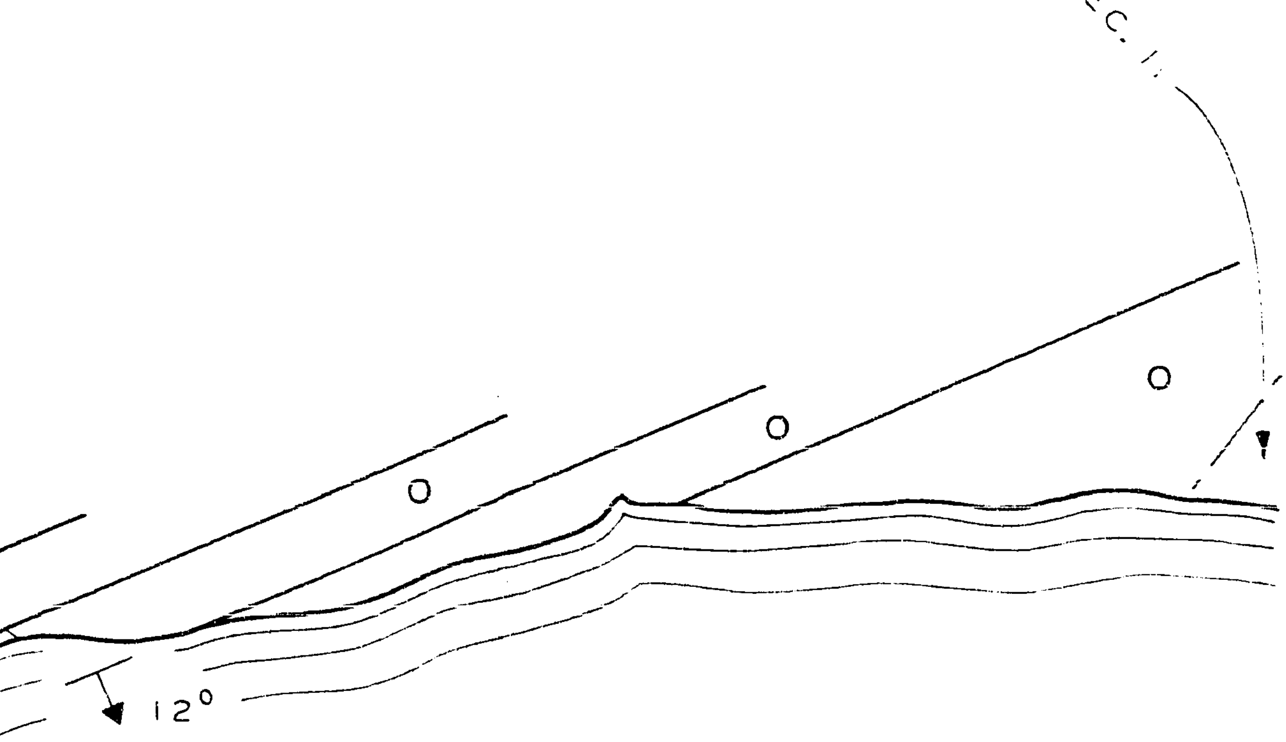

J
SEC. 11
O
O
O
12°


SEC. 20
MILE POST 22
LARSMONT
O
O
12°


2 N - R11 W
SEC. 16
SEC. 21
DULUTH AND
LARSMONT
12°


ON
MILE POST 23
O
O
O
LAKE SUPERIOR




EC. 1
O
O
O
12°