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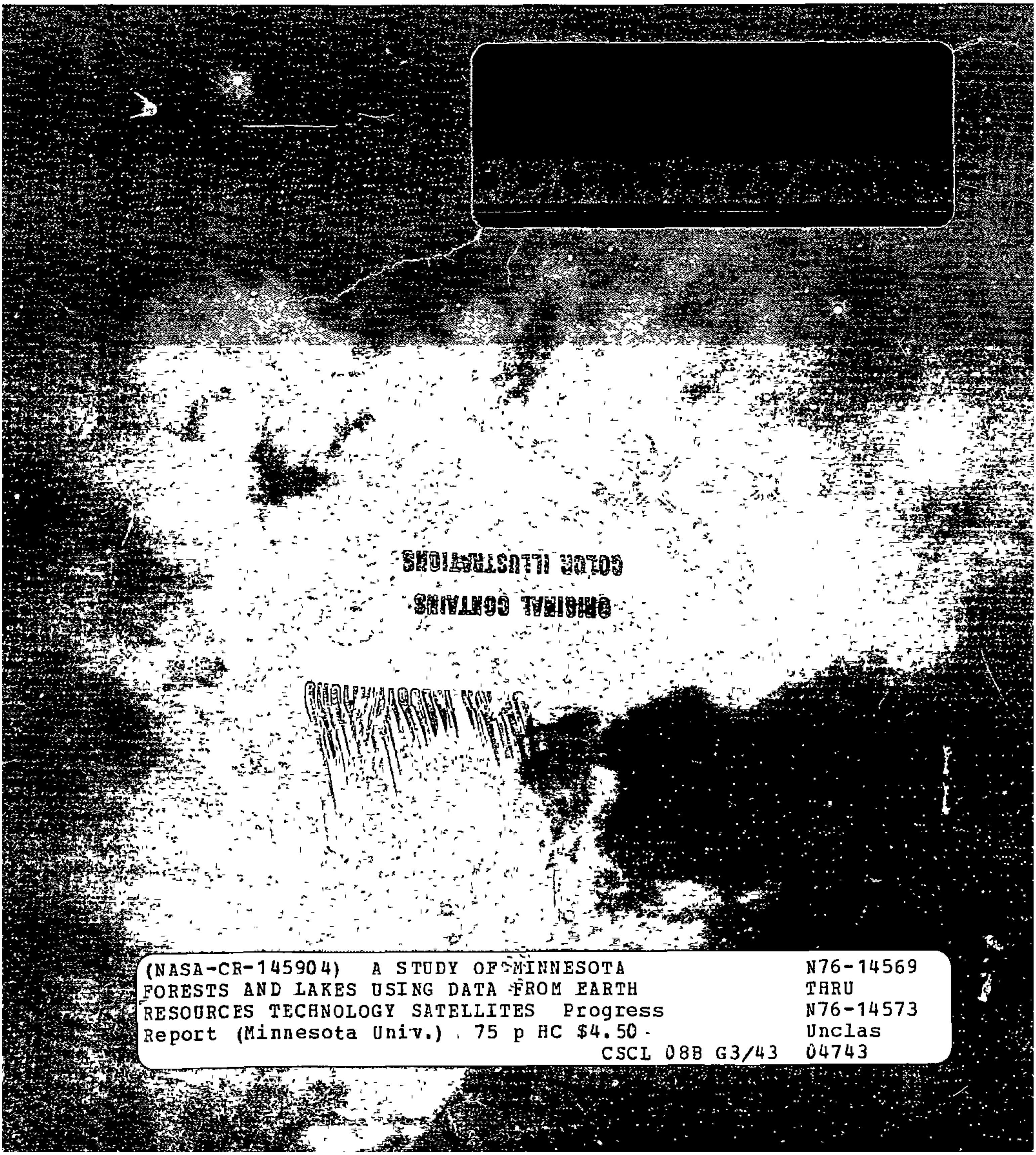

(NASA-CR-145904) A STUDY OF MINNESOTA FORESTS AND LAKES USING DATA FROM EARTH RESOURCES TECHNOLOGY SATELLITES Progress Report (Minnesota Univ.) 75 p HC $4.50 CSCL 08B G3/43

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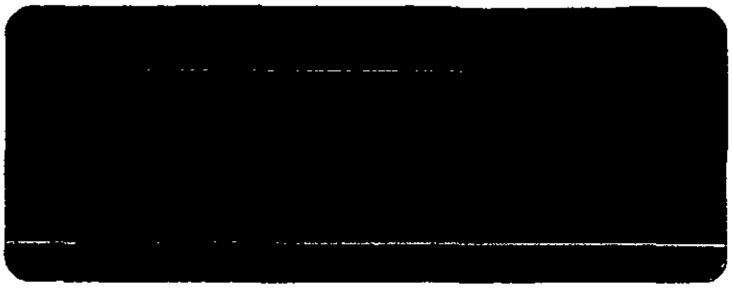
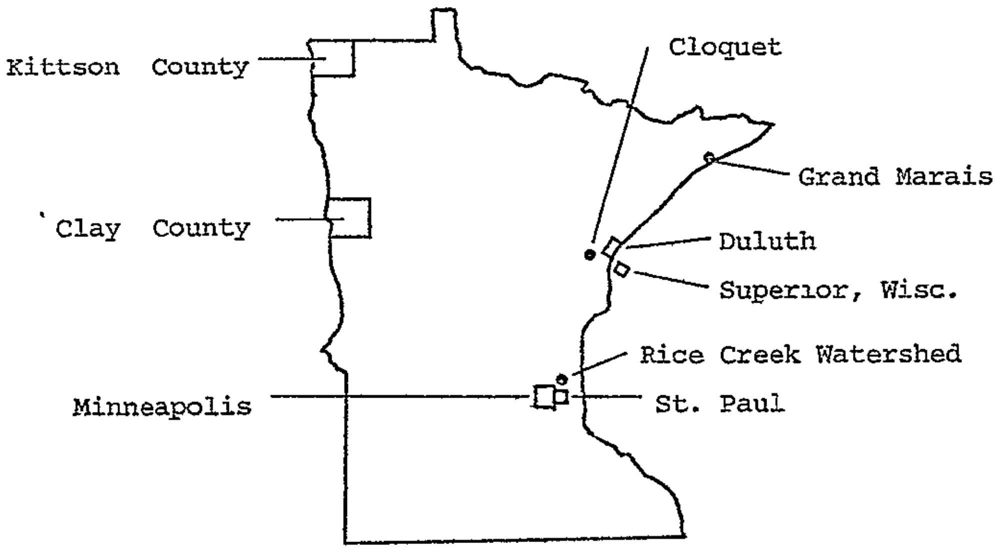


ON THE COVER — The area of the heavens around the Orion Constellation, shown in the cover photograph made through the 120-inch telescope of the Lick observatory, is also the region of observations with an infrared telescope developed by University of Minnesota astro-physicists. The infrared sensory equipment reveals stellar bodies that could not be studied by conventional telescopes, and it is expected to provide data on the birth of stars.

A STUDY OF
MINNESOTA FORESTS AND LAKES
USING DATA FROM EARTH RESOURCES
TECHNOLOGY SATELLITES

June 30, 1975

NASA GRANT NGL 24-005-263



SPACE SCIENCE CENTER

University of Minnesota

Minneapolis, Minnesota 55455

A STUDY OF MINNESOTA FORESTS AND LAKES USING DATA FROM EARTH RESOURCES TECHNOLOGY SATELLITES

THREE-YEAR PROGRESS REPORT

June 30, 1975

Supported by:

NASA GRANT NGL 24-005-263

Submitted to:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546

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SPACE SCIENCE CENTER

THIRD YEAR PROGRESS REPORT

July 1975

INTRODUCTION

This report at the end of the third year of the NASA sponsored remote sensing program at the University of Minnesota is organized into separate individual reports by the individual researchers. During the second year an attempt was made to concentrate efforts on those projects which appeared to be achieving results having practical implications and this direction has been continued during the third year. In accordance with this objective, two programs were phased out during the third year. In the one instance, Dr. Bower's flood prediction which included as a factor ERTS or LANDSAT observations of snow cover, it was felt that while the results permitted some improvement in the flood prediction, the benefits were not sufficient to warrant continuation of the effort. Dr. Mace's studies on the evaluation of water quality by remote sensing techniques have been brought to a conclusion. This study produced results on the optimum film-filter combinations for aerial photographic surveys of the subject lake - Minnetonka. Any further work along these lines should be carried on under the auspices of the State of Minnesota.

A new group headed by Dr. Matt Walton of the Minnesota Geological Survey, which is an operational unit of the University of Minnesota, received support during this year and has obtained results which the Survey feels will bring a new dimension to its geological mapping of the State of Minnesota. They have been sufficiently encouraged by the results obtained during the past year to feel the desirability of adding an individual trained in the use of LANDSAT data to the staff of the Survey. Of particular interest in this effort has been the integration of earlier ground truth geology of segments of the Duluth Gabbro into an integrated whole. These observations have important implications for the mineral development and related environmental problems in the Northeast Region of Minnesota. The demonstrated usefulness of LANDSAT data in the geological mapping of this area suggests that better maps can be produced at much lower cost than has previously been possible. The results have enabled them to pinpoint areas where ground party surveys should be sent in to verify information suggested by the LANDSAT Imagery. A second part of the effort of Dr. Walton's group explored the utility of LANDSAT Imagery in mapping the complex glacial drift overburden which is so significant in the surficial geology characteristic of the State of Minnesota. To test this hypothesis, LANDSAT Imagery of the Twin Cities metropolitan area was investigated to compare results obtained with this technique with the rather extensive ground truth data available in an area which has been more completely studied than most of the other parts of the State. The results of this metropolitan study suggest that LANDSAT techniques can be used as a reconnaissance tool for a statewide project.

The Lake Superior study program conducted by Professor Sydor has been brought to a stage where the results have found a useful application by the U. S. Army Corps of Engineers in determining on-lake dumping sites for dredgings of Duluth Harbor which would minimize the effects on the water intake of the cities of Duluth, Cloquet and Superior. His work has clarified the effects of erosion of the Wisconsin red clay banks on the turbidity of the lake under various wind conditions. Because the red clay arises from a distributed source, the resulting turbidity is different from that which results from turbidity produced by point sources such as the outlets of the Lake Superior Harbor. The combination of these studies led to the recommendations to the U. S. Army Corps of Engineers for more suitable locations for on-lake dumping sites than those used previously. Included with Dr. Sydor's report is the correspondence with the U. S. Army Corps of Engineers relative to the identification of newer dumping sites and the decision to abandon the previous dumping sites which had deleterious effects on the water quality at the intakes of the three cities.

Drs. Dwight Brown and Richard Skaggs have incorporated in their report decisions on land use made by the Rice Creek Board of Watershed Managers based on results previously obtained about the Rice Creek watershed derived from NASA high altitude aerial photography.

As a second effort, Brown and Skaggs have carried on a LANDSAT based surface water inventory aimed at investigating seasonal changes in visible open water. In order to test the utility of these techniques, they studied the St. Paul-Minneapolis metropolitan area lakes because of the extensive ground truth data available. Their work is of particular interest to the Minnesota Department of Natural Resources whose personnel must deal with permits and enforcement with respect to State regulations about the management of land surrounding lakes and the possible drainage of shallow lakes. These data can also be useful to the Department of Natural Resources in their wildlife management responsibility. The surface water inventory is illustrated by the maps that appear in the appendix. It appears that LANDSAT mapping of this type can provide very significant economies as compared to earlier techniques employed by the Minnesota Department of Natural Resources. This technique has been accepted and will be supported by the State Planning Agency. Drs. Brown and Skaggs have assisted in the transfer of the capability to that Agency which is working in cooperation with the State Regional Development Commissions on its application to their planning efforts. During the past year they have also directed a new effort toward the development of techniques for a reconnaissance survey of Minnesota lake water quality from LANDSAT data. The objective is to determine whether these techniques will make it possible to identify easily and cheaply those lakes whose water quality has been degraded where remedial action or conservation measures are especially needed. Such information is of interest to the Minnesota Pollution Control Agency. The multi-spectral reflectance data collected by LANDSAT systems suggest that the techniques have promise as a quick, low cost, reconnaissance tool for investigating lake water quality in Minnesota.

During this year Dr. Rust has completed his studies aimed at the identification and delineation of saline soil areas in the Northern Red River Valley area of Minnesota. Earlier studies had suggested that the clearest delineation of these saline soil areas occurred if infrared imagery was obtained at approximately "peak of green" condition for the small grains. The three years of photography has provided imagery of a growing crop on nearly all of the areas studied. This work has resulted in the capability to delineate on the Soil Association map of Kittson County the saline areas. That information will be included as a part of the County soil report of the National Cooperative Soil Survey scheduled for publication in 1977. Such a map can be used to guide the planting decisions of the farmers in the affected areas. It also could be used in the assessment of the value of farm lands in the area.

Dr. Rust also has included a preliminary report on the application of color infrared imagery to on-farm surveys in Clay County Minnesota. It is planned that the results will be used to provide guidance to field scientists in providing accurate and detailed soil maps which will form the basis for land use and management recommendations by the County technical people to farm operators.

Support was also given to projects under the direction of Dr. David W. French and Dr. Merle P. Meyer. Dr. French's project was concerned with the application of remote sensing techniques to the detection of Forest and Urban Tree Disease in order that forest management practices and remedial steps can be planned and implemented to minimize the spread of the diseases. Dr. Meyer's project is more directly aimed at the use of remote sensing techniques for forest land management.

A number of circumstances delayed much of the field work planned by these two investigators for the operational season of 1974 with the result that much of it had to be carried over into the operational season of 1975 and combined into the work plan for the latter season. The conditions of the 1975 operational season have been unusually favorable and such that field operations have been possible for a much longer period than normal. As a consequence their analysis of their results was postponed and this has delayed their report. Their reports will be submitted as a supplement to those included herein.

SECTION I

REMOTE SENSING APPLICATIONS TO HYDROLOGY IN MINNESOTA

Drs. Dwight Brown and Richard Skaggs
Department of Geography
University of Minnesota, Minneapolis

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REMOTE SENSING APPLICATIONS TO HYDROLOGY IN MINNESOTA

Investigators: Dr. Dwight Brown & Dr. Richard Skaggs
Department of Geography
University of Minnesota, Minneapolis

INTRODUCTION

This research effort has been directed toward developing applications of NASA remote sensing products to information needs in Minnesota related to surface water resources. In our last report we described completed projects for the Rice Creek Board of Watershed Managers and the detection of surface water and surface water changes described by Prestin (1974). As a follow-up on Prestin's work, techniques were established to produce low-cost U.S.G.S. quadrangle overlays of LANDSAT verified surface water. In the past year, 45 quadrangles of the St. Paul - Minneapolis Metropolitan Area, designated a high priority study area by the Minnesota Department of Natural Resources, were completed.

Evaluation of this project and the initiation of studies of the use of LANDSAT 1 imagery as a tool for reconnaissance analysis of lake quality comprised the rest of the effort during the past year. In addition, we include a brief review of the decisions made by the Rice Creek Board of Watershed Managers in which data derived from NASA high altitude aerial photography contributed to the decision making process.

RICE CREEK WATERSHED STUDY RESULTS

A wide variety of land and water resource decisions have been made by the Rice Creek Board of Watershed Managers using the Rice Creek Watershed land use map based on NASA high altitude photography. Of the 15 to 20 actions taken to date, two were selected for illustration here as representative of the types of decisions being made on an ongoing basis.

The first example is the decision concerning the development of the low lying southeastern shore of Pike Lake. Figure 1 shows the area involved in the decision. A computer model, with runoff coefficients derived from the Rice Creek Watershed Land Use Map, was used to determine the height of the 100 year flood hazard zone. The flood zone was determined to be 6 feet above the normal lake level and no basement floors may be constructed below this level. These limitations on this tract enabled the developer to plot 20 single family unit lots. Ten lots with lake frontage were necessarily long because of the flood zone restrictions and the need for a construction site above the flood zone. The flood zone determination enabled land development under the final plat shown in Figure 2. The preconstruction value of the land is now placed at $290,000.

The second example is a decision by the Board of Watershed Managers to require incorporation of several small wetlands in Arden Hills, MN into the drainage plans as pollutant and nutrient sinks rather than being infilled. This decision was based on the existing land use in the contributing area, as mapped using NASA high altitude aerial photography, and the additional impact that intensive cluster home development would have on the nutrient and pollutant load of the Watershed. Figure 3 shows the location of these preserved wetlands.

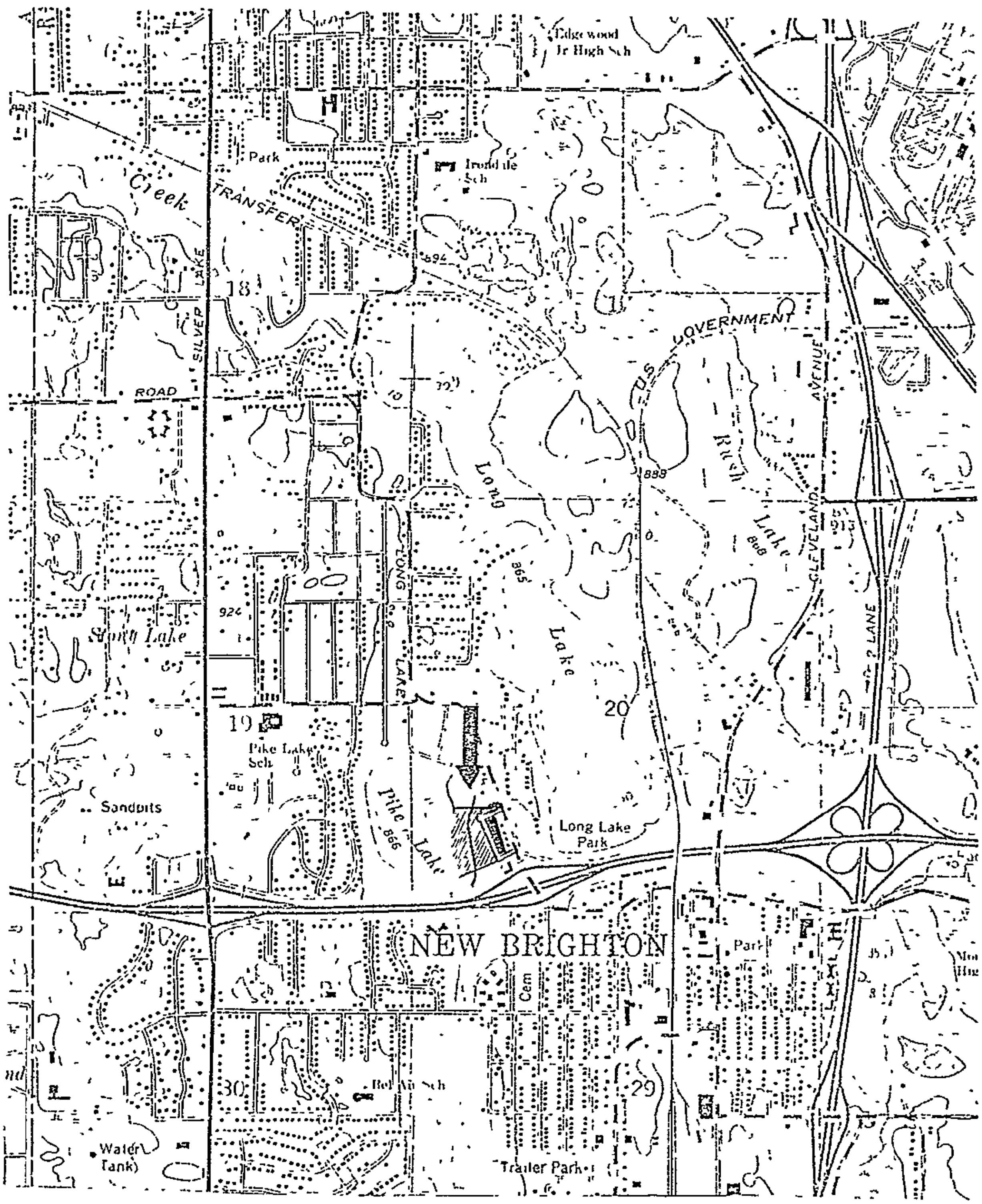

FIGURE 1: The arrow indicates a platted residential area of the Rice Creek Water Shed on Pike Lake. The solid black areas are lots for full development. The diagonal lined area represents lots that encroach on the flood zone designated as six (6) ft. above the 866 ft. lake elevation. The line represents the approximate landward limit of the flood zone.

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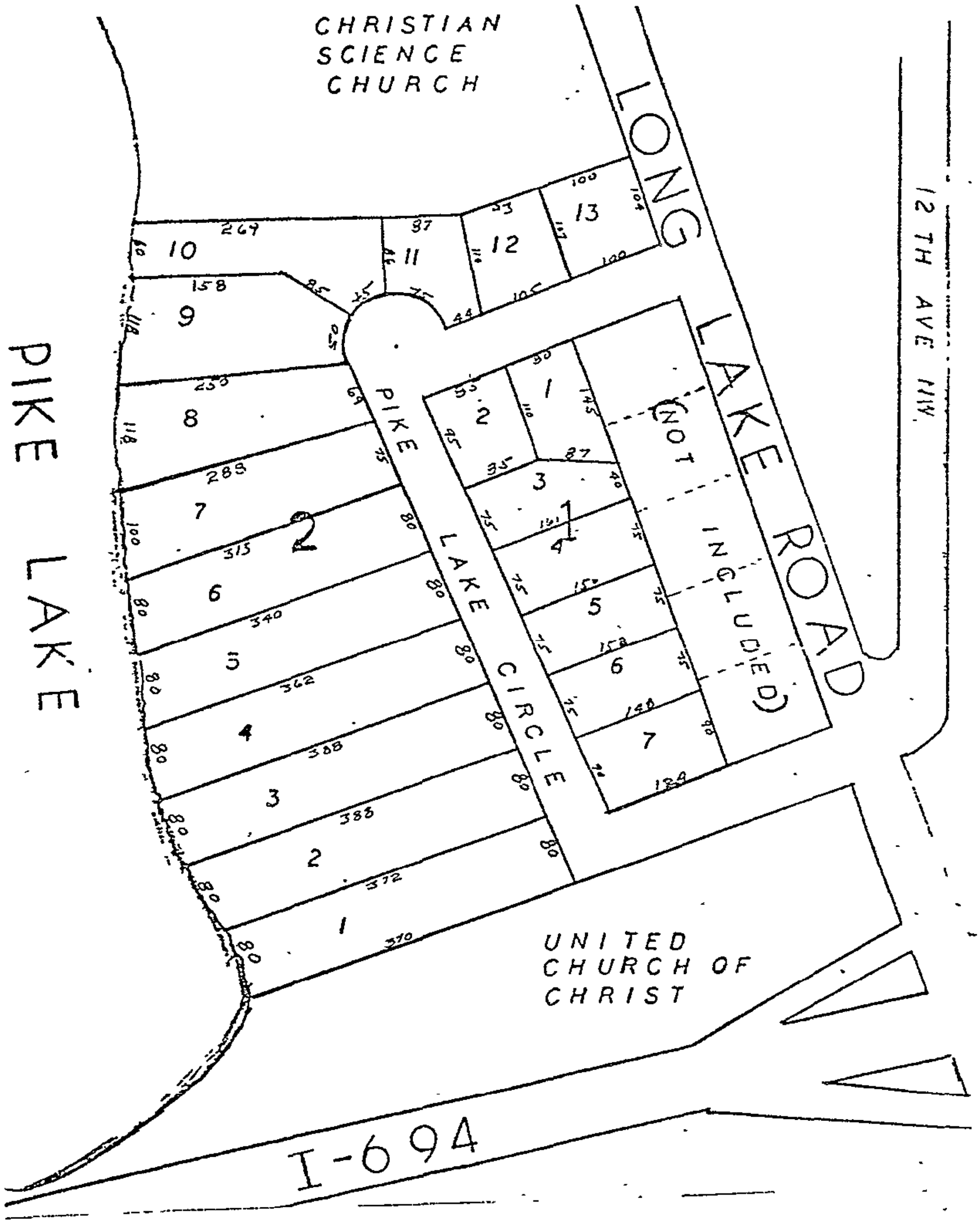

FIGURE 2: Detailed final plat of area shown in Figure 1. Note the length of lots necessary to avoid structures in the flood hazard zone.

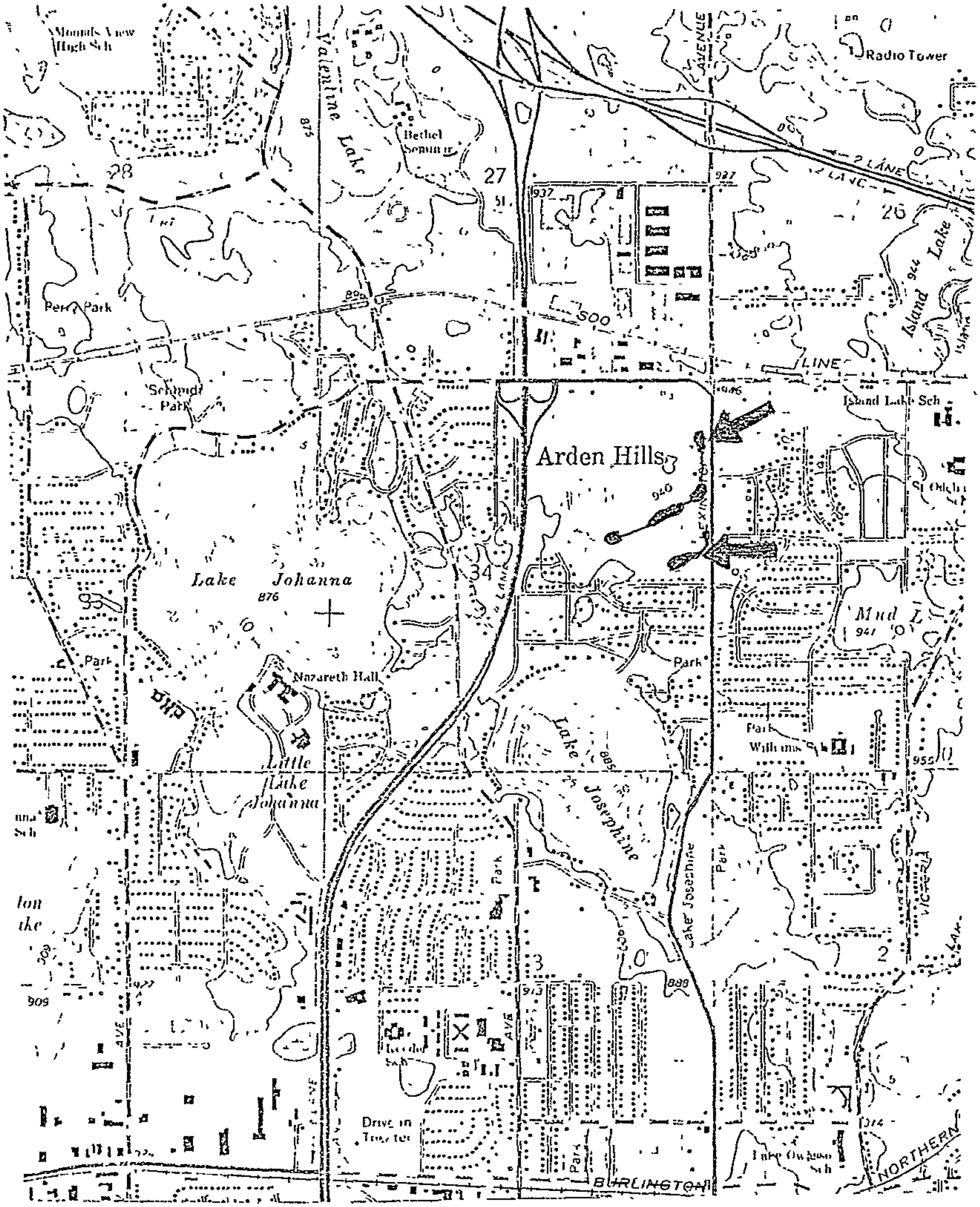

FIGURE 3: The black shading indicated by arrows represents areas of wetlands that have been preserved as pollutant and nutrient sinks in a cluster home development.

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RECONNAISSANCE ANALYSIS OF LAKE WATER QUALITY IN THE ST. PAUL - MINNEAPOLIS METROPOLITAN AREA WITH LANDSAT IMAGES

Introduction

This project is directed toward developing the techniques for a reconnaissance survey of Minnesota lake water quality with LANDSAT data. The St. Paul - Minneapolis Metropolitan Area lakes provide an excellent study area to develop this capability because convenient, low cost, and has a very high density of available ground truth provided by cooperating agencies. The ultimate goal is to provide guidance so that more costly and detailed surface investigations may be directed toward lakes where remedial action or conservation measures are especially needed. Personnel from the Minnesota Pollution Control Agency have expressed interest in this type of data.

In developing the technology for use in Minnesota, we plan to use a variety of available equipment and results of similar studies done elsewhere, particularly work at the Environmental Protection Agency by Boland.

Preliminary Analysis

The first preliminary analysis was carried out using a VP-8 image analyzer to read film densities. The first test employed 9" X 9" black and white LANDSAT MSS bands 4, 5, and 7 transparencies. The density readings from these three bands for June 28, 1974, were used as independent variables along with angle of reflectance, distance from the image center, and lake area. These independent variables were used in a step-wise multiple regression analysis to develop models to examine relationships with several dependent variables of water quality. The dependent variables used were total phosphorous, chlorophyl, water transparency (secchi disc readings), and a water quality index[1] used by Eugene Hickock and Associates, the engineering firm that produced the lake quality data used.

Based on a sample of 42 lakes or bays for a single date, only two of the dependent variables, secchi disc readings and water quality index, produced strongly encouraging results. Summaries of these results are shown in Table 1. It should be pointed out that although total phosphorous and chlorophyl contents were not strongly related to the independent variables at this time, other dates, possibly later in the summer, may produce better results. The regression equations summarized in Table 1 represent a small number of lakes in a limited area at one time period. However, the quality of results is consistent with those produced by Boland (1974) for a national study using digital tape data and is sufficient to encourage expansion of the study to a larger area and multiple time periods. This will be done using data from the Space Science Center densitometer. Some preliminary data collection has been attempted with this equipment but further modifications in the densitometer are likely to be necessary.

During the next year multiple time periods of LANDSAT data will be analyzed with the densitometer. Computer compatible tapes will also be used for a more selective number of time periods to evaluate the best and lowest cost method of obtaining satisfactory results.

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[1] The average of parameters obtained from graphs for secchi disc, orthphospate, ammonia, and pH values resulting from ground truth data available for these lakes.

TABLE 1

SUMMARY OF LAKE WATER QUALITY MULTIPLE REGRESSION ANALYSES

Dependent Variable	Step	Variable entered	B coefficient	Std. error B	Multiple r	r square
Secchi Disk Reading		(constant)	56.4001	6.3665		
	1.	Band 5	-.7451	.0966	.62529	.39098
	2.	Distance from Center of Image	-.6208	.1140	.80277	.64445
	3.	Band 7	8.1200	.0231	.88586	.78475
.... Quality Index		(constant)	-1462.3090	670.0596		
	1.	Band 5	-3.1681	.2204	.67433	.45472
	2.	Distance from Center of Image	-3.0500	.2600	.91656	.84007
	3.	Band 7	.1772	.0586	.95693	.91572
	4.	Angle of Reflectance	34.3706	13.0933	.96905	.93905

INVENTORY AND SEASONAL CHANGE OF OPEN WATER IN THE ST. PAUL - MINNEAPOLIS METROPOLITAN AREA

Introduction

The encouraging results obtained by Prestin (1974) in his effort to map small seasonal water features in west central Minnesota led to the establishment of a LANDSAT - 1 based surface water inventory project. MDNR expressed considerable interest in the project, supplied data format requirements, and designated the St. Paul - Minneapolis Metropolitan Area as a first priority test area.

MDNR personnel dealing with permits and enforcement indicated that the updated water inventory maps should be 1:24,000 or 1:62,500 scale topographic map overlays and should show the extent of LANDSAT verified seasonal changes in visible open water. These transparent quad overlays, produced on stable matte acetate, could be used by field personnel and also serve as a locationally accurate data base for a forthcoming statewide water information system.

Mapping Procedures

Production of LANDSAT verified quadrangle overlays requires three data sources: good quality topographic base maps and good quality LANDSAT - 1 MSS system corrected color transparencies for both the maximum and minimum extent of visible water. The maximum and minimum extent of water was determined from imagery dates between August, 1972, and June, 1974. The selected images were used to produce 35 mm ektachrome quad-centered slides from back-lighted LANDSAT - 1 transparencies. A single lens reflex camera with a through-the-lens light meter and fitted with a 50 mm lens and extension tubes was used to copy areas 3 to 4 times the quadrangle area in order to reduce optical distortion. The topographic maps were mounted on the wall and the slides were projected with a remote focus, zoom lens slide projector. Two person teams greatly speeded up the slide registration and mapping.

The minimum calculated discrepancies between the map and projected image were about .1 inch over a 1:24,000 scale map. With the use of maps other than U.S.G.S. topographic quadrangles, the geometric discrepancies were much greater.

After registering the slide on the wall-mounted topographic map, a stable base drafting acetate, with previously traced U.S.G.S water boundaries was registered over the topographic map. To maximize color contrasts the topographic map was then removed to expose the white wall mounting board.

The first image mapped was the maximum water extent followed by the minimum water extent. When the mapping was complete, the acetate was taken to a drafting table and again registered on the topographic map. The extent and limits of water were then interpreted and corrected on the topographic map, using LANDSAT verified location of water. This procedure enabled the exercise of judgement and allowed the mapping of water by inference in narrows that are not detectable on LANDSAT images. This procedure also minimized the problem of interpretation of plowed fields or cloud shadows as water, because lakes are restricted to very specific topographic locations. These locations have well-defined geometries on the topographic maps that would have a very low order of possibility of being confused with plowed fields or cloud shadows.

In this pilot project the final copies of the 45 quadrangles for the Metropolitan Area were drafted by hand; although for larger projects it might be desirable to digitize the water outlines and produce the final copy with a continuous line plotter. This procedure has distinct advantages if the data are to be digitized for a water information system. The computer driven plotter offers the flexibility of producing maps at a variety of scales and for quadrangles, political units or even complete lakes.

The locations and reduced versions of the topographic quad overlays are shown in the Appendix.

Evaluation

The products are evaluated in three ways: cost effectiveness, comparative accuracy, and degree to which they meet data needs for surface water inventory of MDNR. We produced the first two evaluations, and the third is provided by MDNR.

Table 2 shows the cost of mapping the 45 Metropolitan Area quadrangles and, assuming these are representative for the entire state, projects them for estimated costs to completely map the state. Labor requirements for the Metropolitan Area quads varied from 5.25 to 22.25 man hours depending on the number and complexity of lakes and on the scale. The 1:62,500 scale quads took nearly four times as long to complete because they covered four times the area. In calculating the costs for the state, it could be assumed that there will be a slight reduction in the per unit costs as the area increases. Equipment costs would be under $2,000 for an operation large enough to complete the job in one calendar year.

This is particularly significant in view of the more than a decade

TABLE 2

MAPPING LAKES FROM NASA/ERTS IMAGERY

Cost Projections:

Area	7.5' quads (1:24,000)	15' quads (1:62,500)	Total Man Hours	Labor Costs at $7/hr	Total Supply Costs	Total Costs
1) Metropolitan Mpls-St. Paul	33	12	585	$4095	$1000	$5095
2) State of Minnesota	1105	134	10625	$74375	$21000	$95375

spent to complete MDNR's Bulletin 25, "An Inventory of Minnesota Lakes." The cost of producing Bulletin 25 was probably in excess of $400,000. These costs should be kept in mind when comparing the LANDSAT-based quad inventories of lakes with Bulletin 25.

The ability of interpreters to discriminate surface water features from LANDSAT images is well outlined by Prestin (1974). Table 3 summarizes Prestin's results, comparing different LANDSAT (ERTS) products with Bulletin 25 and 1968 high altitude panchronmatic aerial photography. Because the bases of comparison are not compatible in time, they provide only a crude evaluation; however, it is very instructive to look at the total comparative results for various ERTS products. Single date analysis with color imagery detected 58 water features as opposed to only 34 in Bulletin 25, and an ERTS inventory using seven periods of time from August 16, 1972, through July 5, 1973 detected 177 different water bodies. It should also be noted that Bulletin 25 is really an inventory of lake basins which may be partially or entirely dry. It therefore might be considered as a seasonal maximum of water area for basins of ten acres or more.

To evaluate the comparative accuracy of quad scale lake mapping for the Metropolitan Area, the mapped lakes were examined on an individual basis to determine which lakes were not included in Bulletin 25 and which lakes in Bulletin 25 were dry or had a substantially reduced water area. The results are summarized in Table 4. It is readily apparent that the water status of basins in Bulletin 25 is, at best, poorly known. In addition, there is a 13% increase in the number of basins as defined by water features for which there are no listed basins. Many of these were either accidentally omitted or considered not to meet the criteria

TABLE 3 -- NUMBER AND ACREAGE OF HYDROGRAPHIC FEATURES

OTREY TOWNSHIP

Source		Size Classes (acres)							
		0-4.9	5.0-9.9	10.0-14.9	15.0-19.9	20.0-74.9	75.0-199.9	200.0	Total
Bulletin #25 Basins	Number	-	-	3	6	17	5	3	34
	Acres	-	-	38.0	102.0	669.0	472.0	1250.0	2531.0
'68 High Altitude-Water	Number	7	7	9	5	12	1	2	43
	Acres	23.2	52.2	117.6	83.6	634.9	180.8	888.4	1980.7
ERTS Inventory Water	Number	33	66	33	14	28	1	2	177
	Acres	112.9	443.7	405.3	245.2	693.9	166.4	764.3	2831.7
ERTS 16 Aug. '72 Color Water	Number	1	29	7	4	14	1	2	58
	Acres	4.5	219.4	86.3	71.0	534.0	165.1	686.7	1767.0
ERTS 16 Aug. '72 Band 7 - Water	Number	5	9	8	2	11	1	2	38
	Acres	19.7	58.9	100.0	35.2	383.3	163.2	686.7	1447.0

of a defined basin. On the other hand, some of these are new, man-made basins.

The apparent discrepancy between water features mapped with LANDSAT images and Bulletin 25 result from two important factors. First, the production of Bulletin 25 used existing aerial photography which varied in season of coverage from county to county. Second, some of the large-scale stereo photography used is now between 21 and 25 years old.

Brief evaluation of the degree to which the LANDSAT based quad overlays satisfied data needs was provided by MDNR personnel. In current operations the major benefit of the overlays would be to detect water-filled basins that were dry at the time of aerial photography. If used in this way, it could be used as a means of updating Bulletin 25. It was also felt that the greatest value of the overlays might accrue from their use by counties and as a tool in zoning shoreland, particularly in identifying the amount of setback required for the development of highly fluctuating lake shore. These materials could also be used in shoreline classification in MDNR's Shoreland Management program. Finally, overlays for very old quadrangles provide a good basis for beginning water inventories where existing map information and reality bear no resemblance.

On the negative side, the quad overlays fail to show basins (type 3 wetlands) that have no open water surface. The fact that lake basin inventory projects are now underway in MDNR is seen as a limitation for the use of LANDSAT materials for this purpose because it would mean a change in the technology in midstream.

TABLE 4 -- COMPARISION OF ST. PAUL - MINNEAPOLIS METROPOLITAN AREA MAP

WITH AN INVENTORY OF MINNESOTA LAKES, BULLETIN 25

County	Mapped Lakes 10 acres not in Bulletin 25	Number of Basins in Bulletin 25	Mapped Lakes 10 Acres Listed in Bulletin 25 as Not Affected by Drainage or Dry		Mapped Lakes 10 Acres Listed in Bulletin 25 as Affected by Drainage or Dry			
			Reduced in Size	Empty Basins	Total Listed	Affected but Wet	Reduced in Size	Empty Basins
Anoka	15	143	1	6	55	31	7	17
Carver	30	128	0	1	73	25	5	43
Dakota	16	83	2	1	8	2	0	6
Hennepin	32	200	2	12	39	18	3	18
Ramsey	14	82	4	1	31	6	6	9
Scott	14	144	0	6	92	36	3	53
Washington	5	168	1	6	6	3	1	2
Metropolitan Area Total	126	948	10	33	304	121	25	148

Barriers to the utilization of LANDSAT based materials in ongoing projects appear to be primarily normal resistance to change rather than rejection of materials based on their quality. This appears to be especially true where alternate data sources now exist.

SUMMARY

Although the three projects included in this report are at different stages of completion, a summary of their findings is offered as a conclusion.

1. Land use maps of the Rice Creek Watershed have proven useful for a variety of resource allocation decisions, the dollar benefit of which is difficult to assess.
2. Multispectral reflectance data collected by LANDSAT systems appears to provide some promise as a quick, low-cost reconnaisance level tool for investigating lake water quality in Minnesota.
3. Quadrangle overlays of surface water, verified using LANDSAT images, appears to be useful for a variety of purposes by counties and MDNR. However, obstacles to their immediate use in the agency appear to be primarily resistance to change rather than rejection based on the validity of information.

Obviously some further work is necessary in the area of water quality applications. We do need a more penetrating review of the quad overlays produced for MDNR than we have been able to elicit to date.

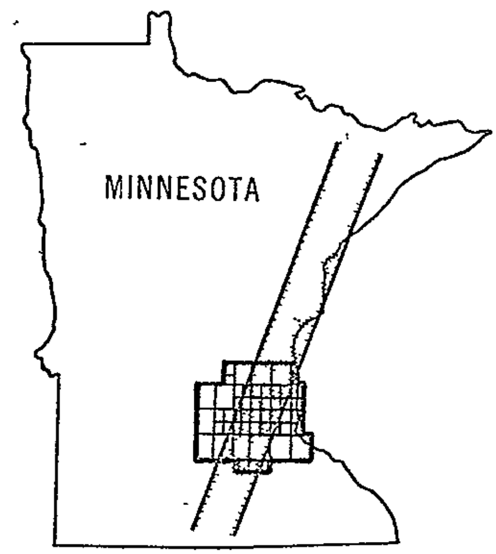
REFERENCES

Prestin, Steven, 1974, "Management of Hydrographic Features in West-Central Minnesota from ERTS-1 Imagery" pp. 99-196 in A Study of Minnesota Forests and Lakes from Earth Resources Technology Satellites, University of Minnesota Space Science Center, June 30, 1974.

Boland, D. H. P., 1974, An Evaluation of the Earth Resources Technology Satellite (ERTS-1) Multiple Scanner as a Tool for the Determination of Lacustrine Tropic States, Ph.D. Thesis, Oregon State University, Corvallis, 289 pp.

APPENDIX

MAPS OF SEASONAL CHANGES IN OPEN WATER
IN THE ST. PAUL -- MINNEAPOLIS
METROPOLITAN AREA

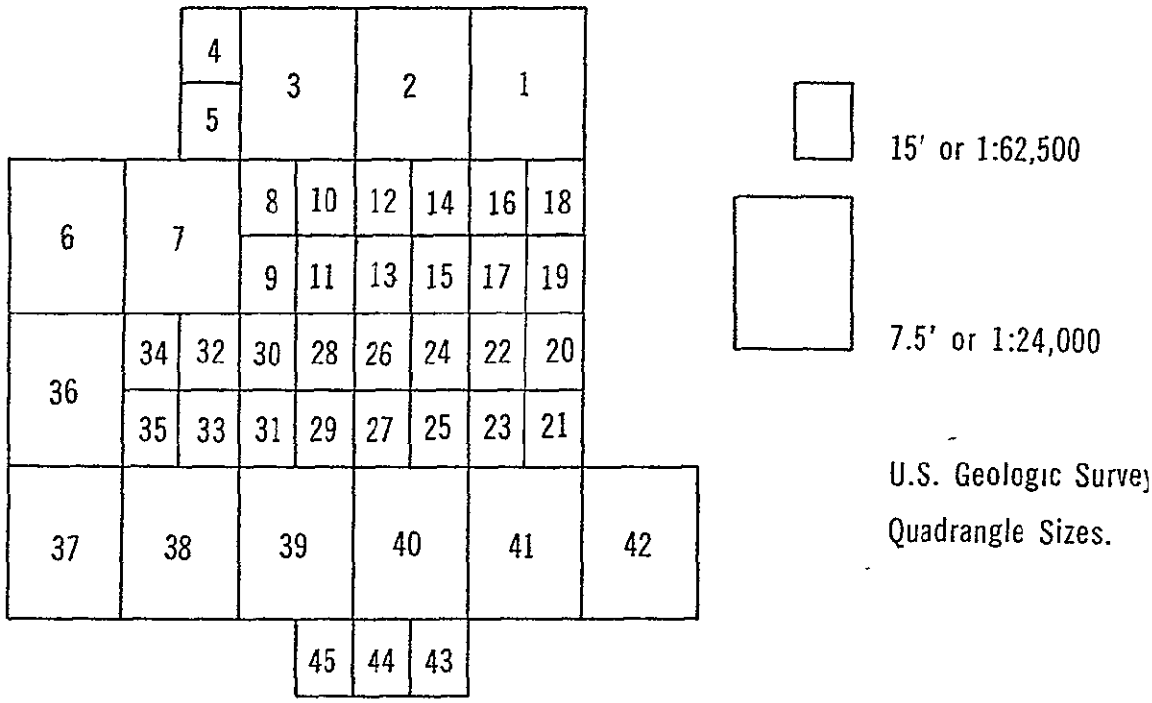


Images Used : ERTS – Color Transparencies
1075–16324, October 6, 1972;
1309–16325 May 28, 1973.

ERTS – 1 Flight Line

LOCATION OF STUDY AREA

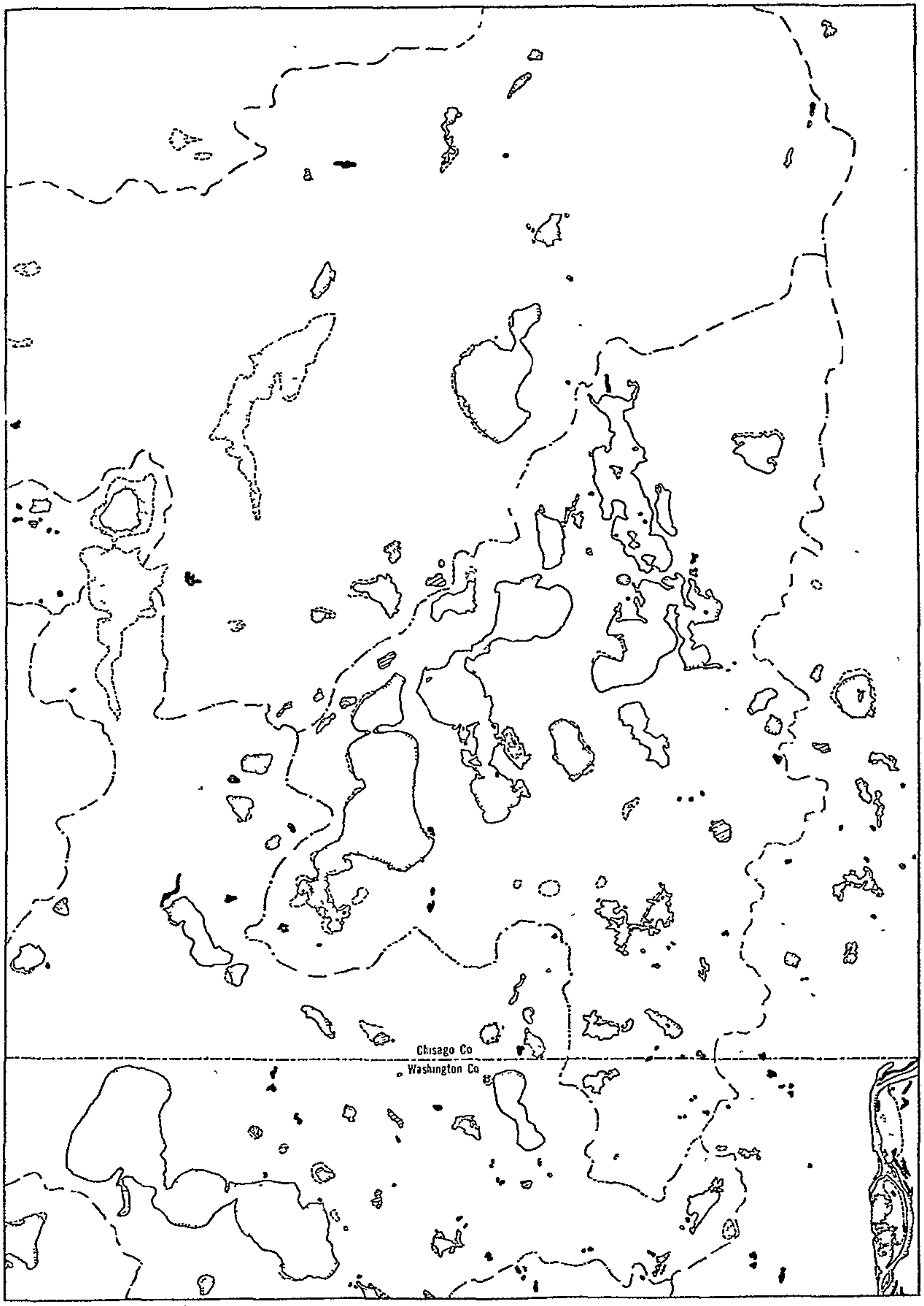
QUADRANGLE INDEX



1. Forest Lake
2. Isanti
3. St. Francis
4. Lake Fremont
5. Elk River
6. Buffalo
7. Rockford
8. Anoka
9. Osseo
10. Coon Rapids
11. Minneapolis North
12. Circle Pines
13. New Brighton
14. Centerville
15. White Bear Lake West
16. Hugo
17. White Bear Lake East
18. Marine on St. Croix
19. Stillwater
20. Hudson
21. Prescott
22. Lake Elmo
23. St. Paul Park
24. St. Paul East
25. Inver Grove Heights
26. St. Paul West
27. St. Paul SW
28. Minneapolis South
29. Bloomington
30. Hopkins
31. Eden Prairie
32. Excelsior
33. Shakopee
34. Mound
35. Victoria
36. Waconia
37. Belle Plaine
38. New Prague
39. Prior Lake
40. Farmington
41. Hastings
42. Red Wing
43. Dennison
44. Northfield
45. Little Chicago

FOREST LAKE QUADRANGLE, MINN.

CHANGE OF VISIBLE OPEN WATER



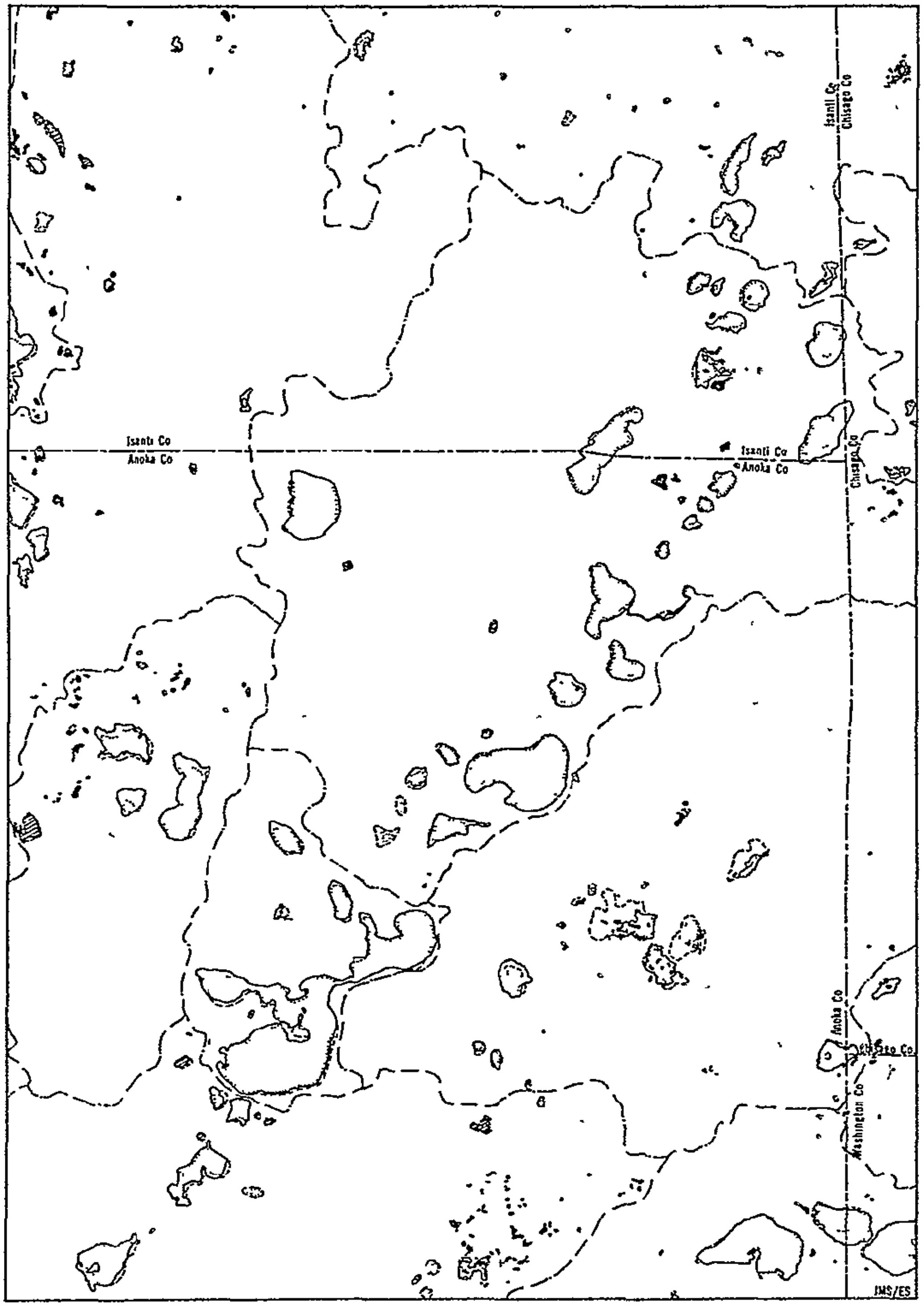
1 mile

Source ERTS satellite photographs

- County boundary
- Lake boundaries 1955 U S G S Topographic Sheet
- Undetectable but existent on U S G S sheet
- Detectable on 10 6 72 only
- maximum visible change 10 6 72
- minimum visible

ISANTI QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



0 1 2 mile

Undetectable but existent on U S G S sheet

Detectable on 10-6 72 only

County Boundary

Watershed Boundaries

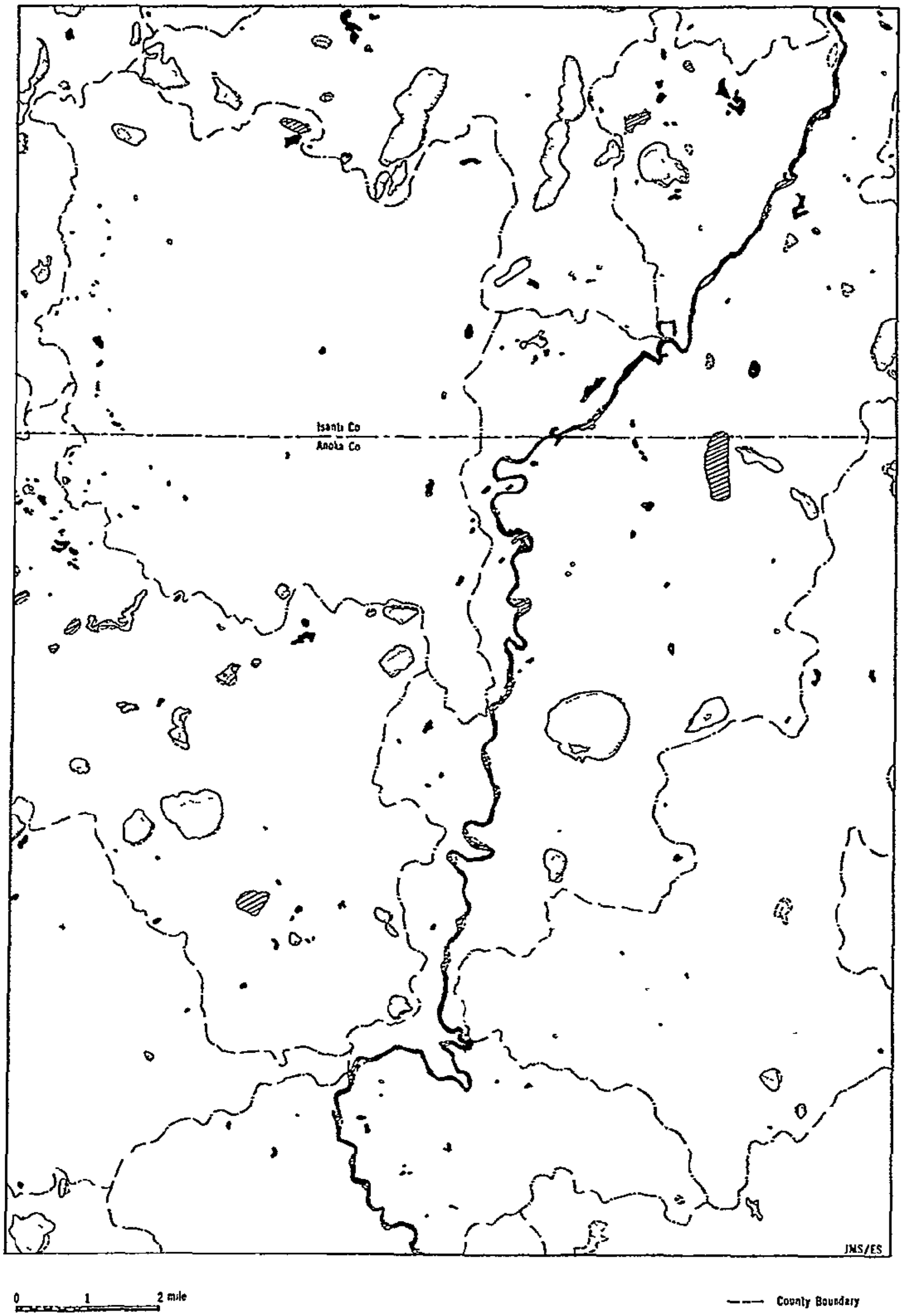
Lake Boundaries 19[illegible] U S G S Topographic Sheet

Maximum visible open water 10-6-72

Minimum visible open water 7-3 73

Source ERTS MSS Imagery

ST. FRANCIS QUADRANGLE, MINN.
CHANGES OF VISIBLE OPEN WATER



— — — County Boundary
— — — Watershed Boundaries
——— Lake Boundaries 19/6 U.S G.S. Topographic Sheet
------ Maximum visible open water 10-6-72
Minimum visible open water 7 3 73

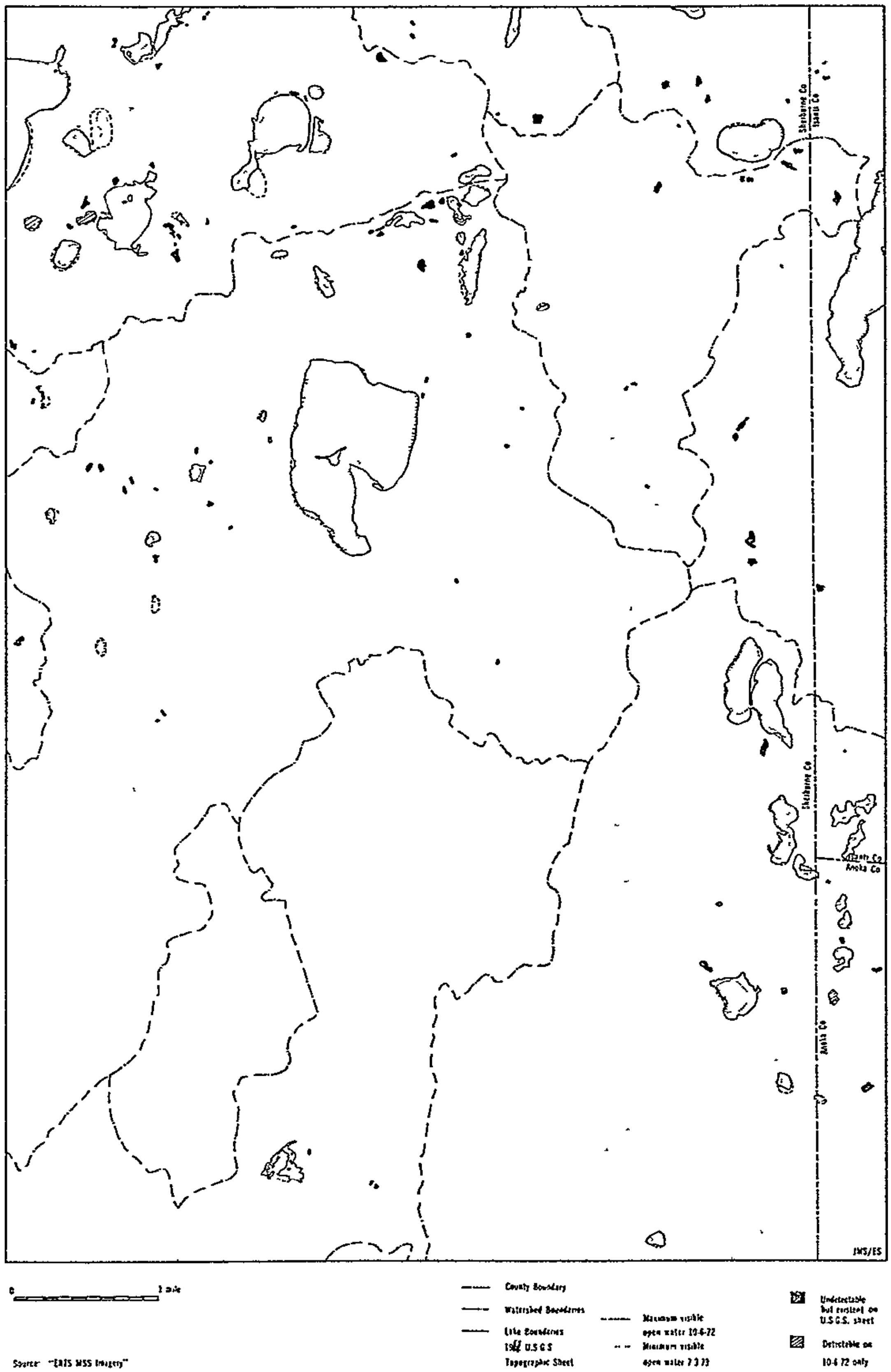
Undetectable but existent on U S G.S sheet

Detectable on 10-6-72 only

Source ERTS MSS Imagery'

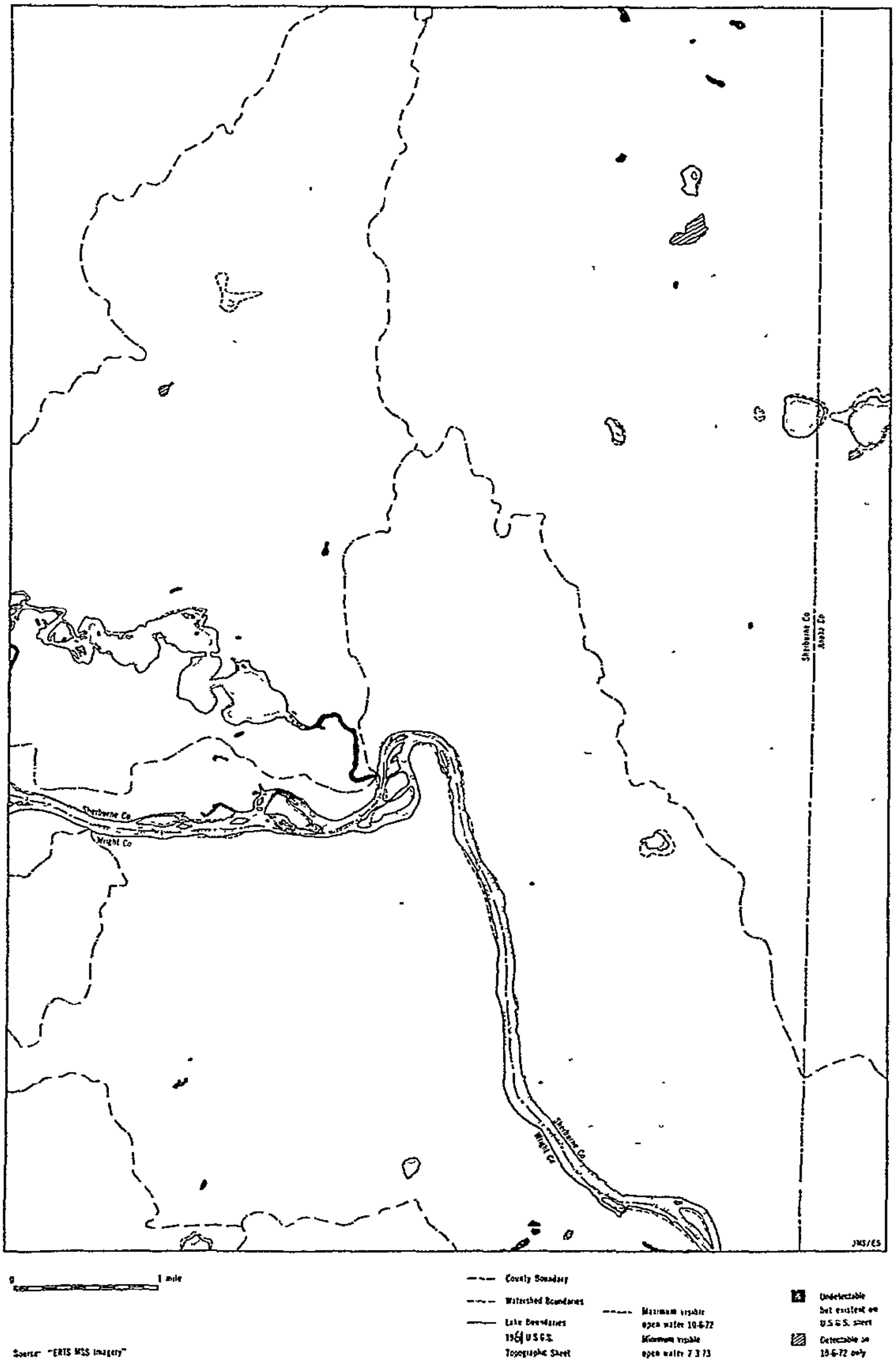
LAKE FREMONT QUADRANGLE, MINN.

CHANGES OF VISIBLE OPEN WATER

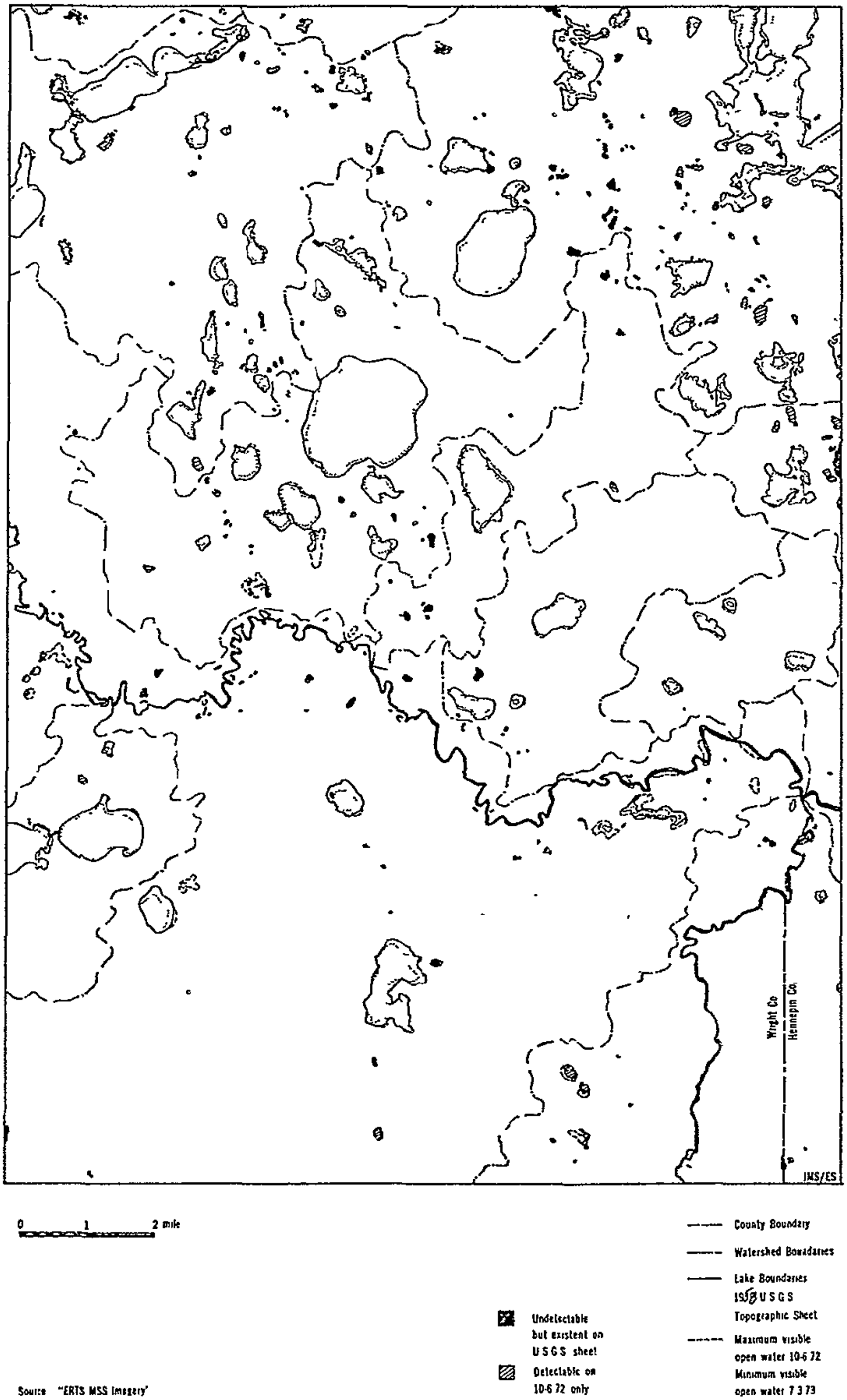


ELK RIVER QUADRANGLE, MINN

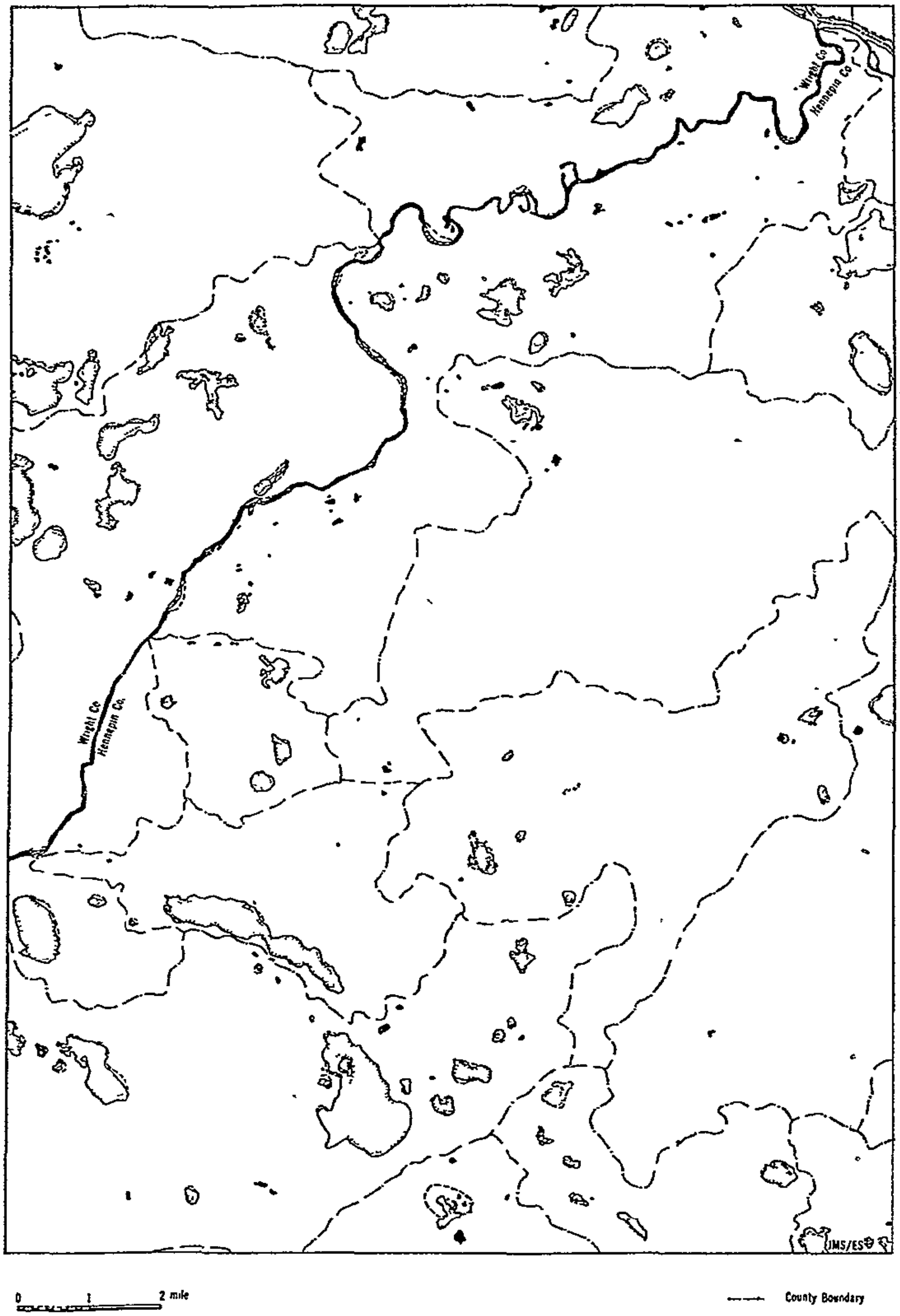
CHANGES OF VISIBLE OPEN WATER



BUFFALO QUADRANGLE, MINN
CHANGES OF VISIBLE OPEN WATER



ROCKFORD QUADRANGLE, MINN.
CHANGES OF VISIBLE OPEN WATER

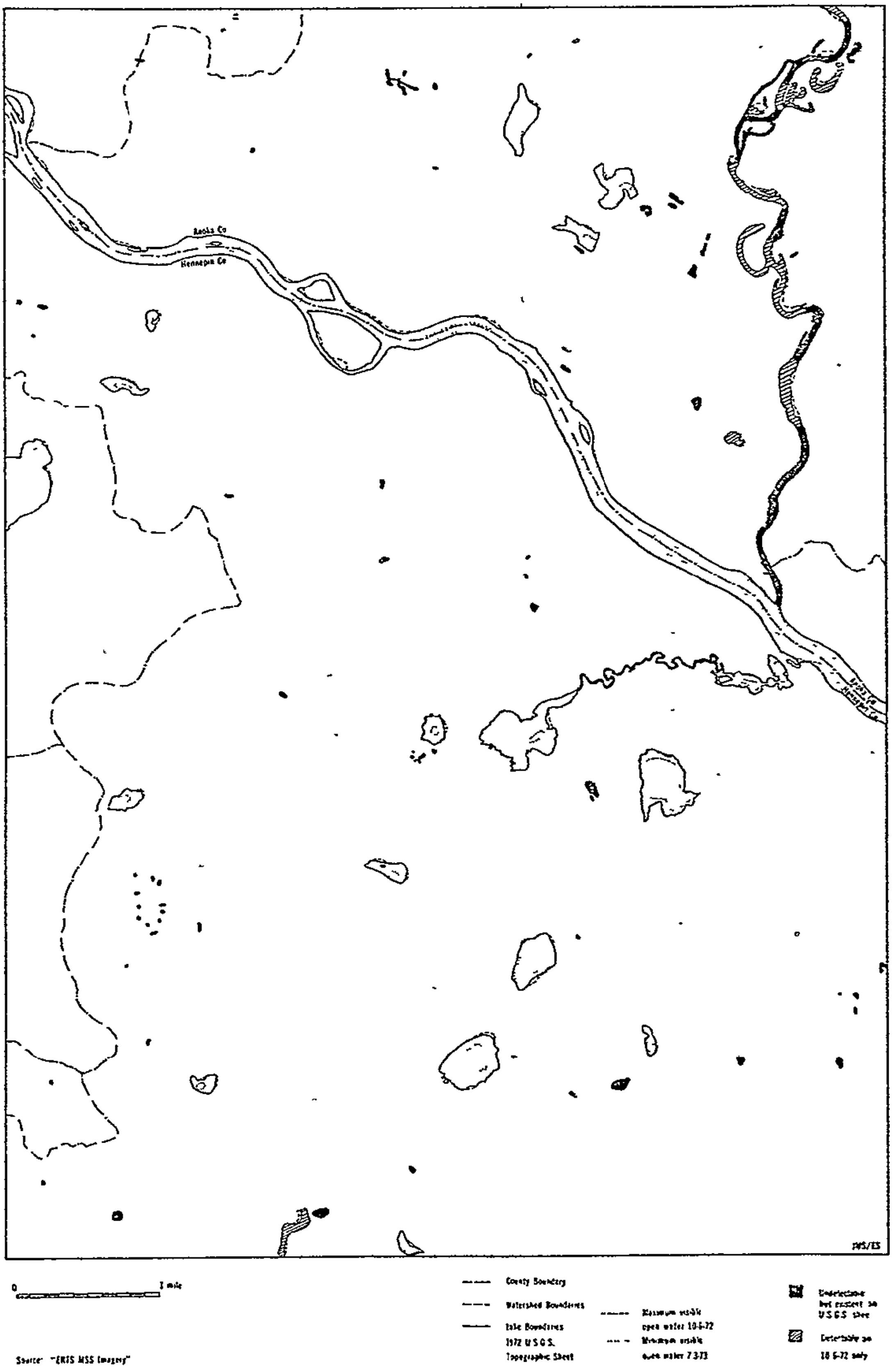


- County Boundary
- Watershed Boundaries
- Lake Boundaries 1958 U S G S Topographic Sheet
- Maximum visible open water 10 6 72
- Minimum visible open water 7-3-73
- Undetectable but existent on U.S G S sheet
- Detectable on 10-6-72 only

Source ERTS MSS Imagery"

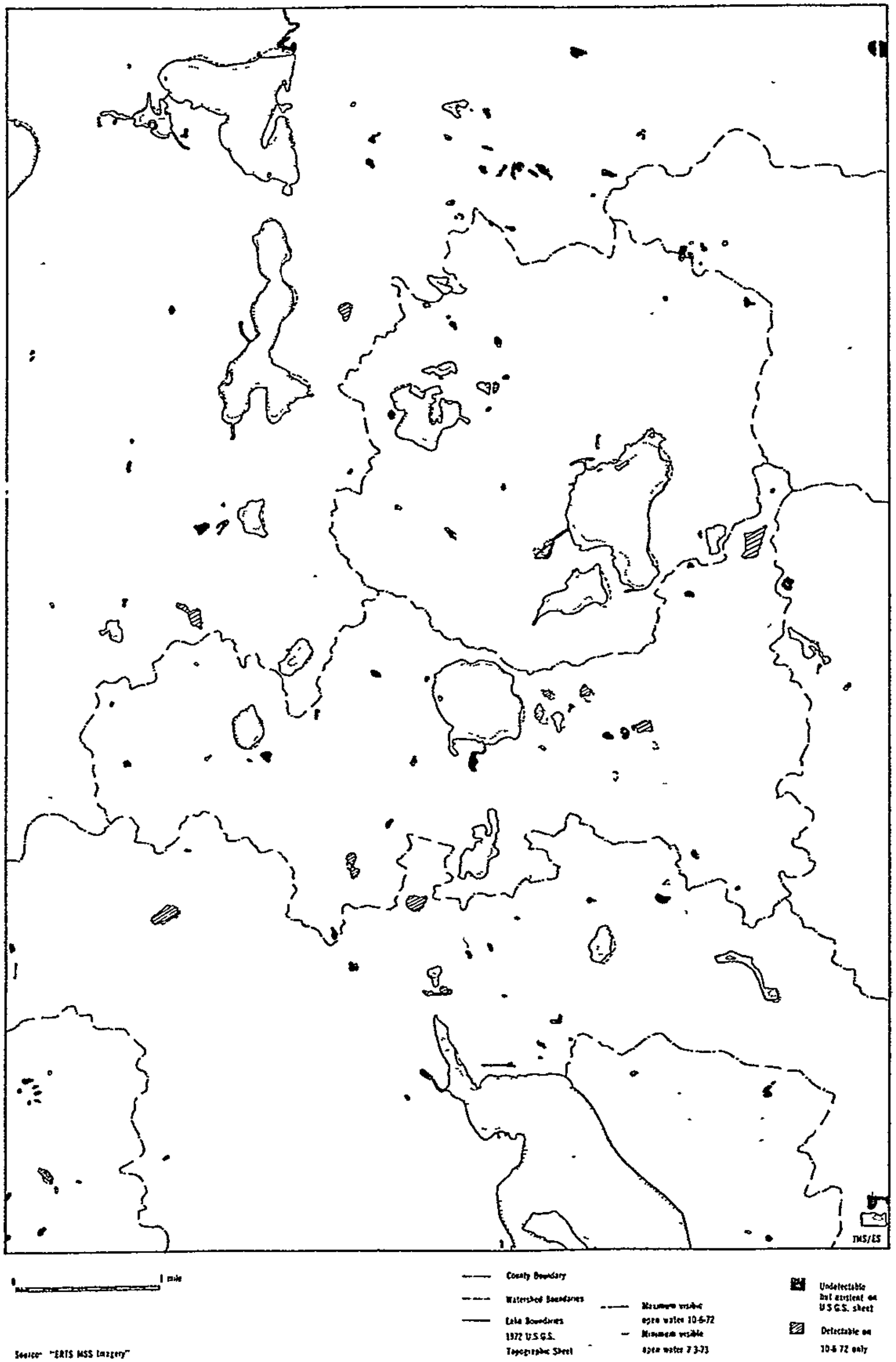
ANOKA QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



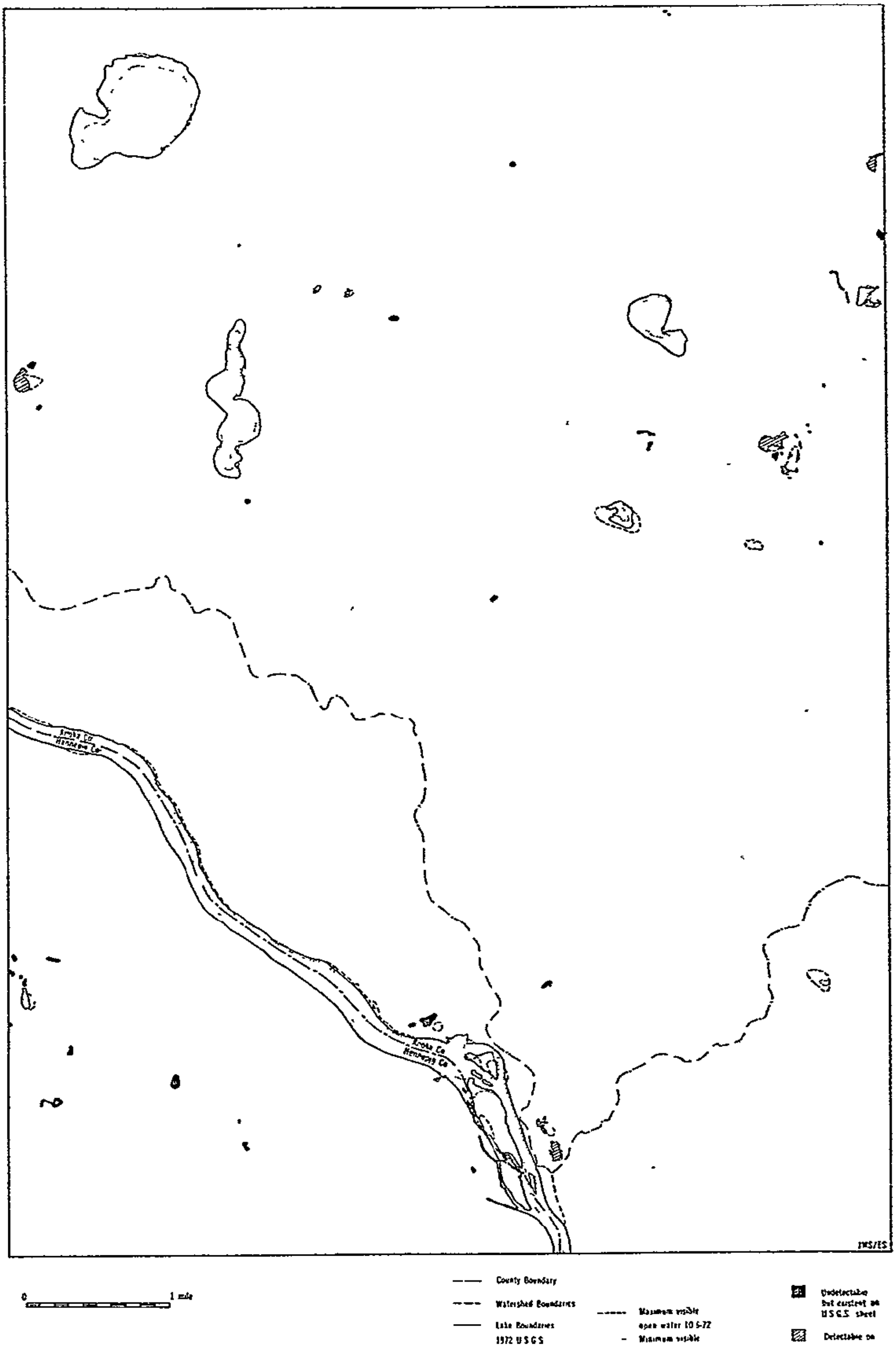
OSSEO QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



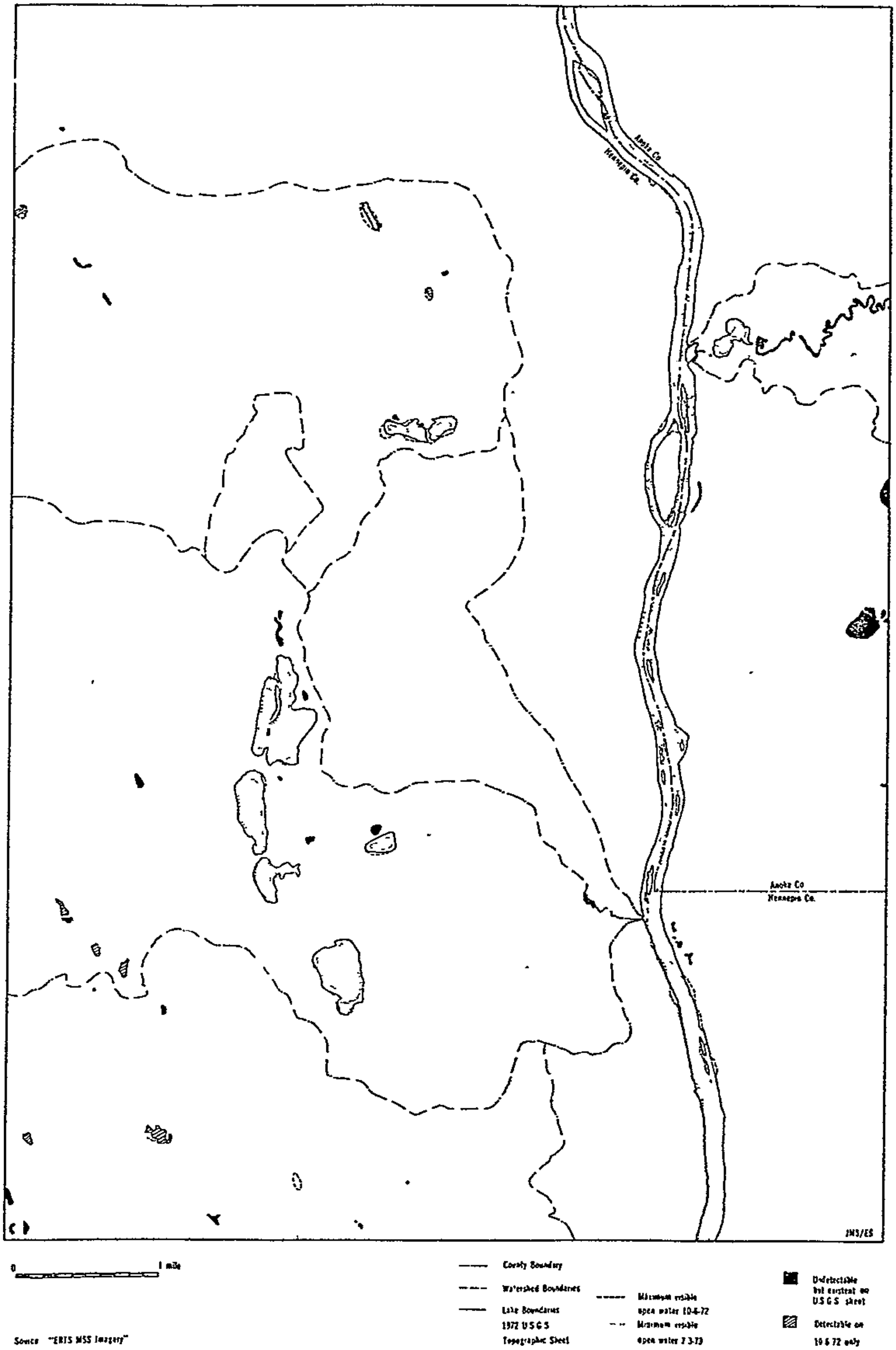
COON RAPIDS QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



MINNEAPOLIS NORTH QUADRANGLE, MINN

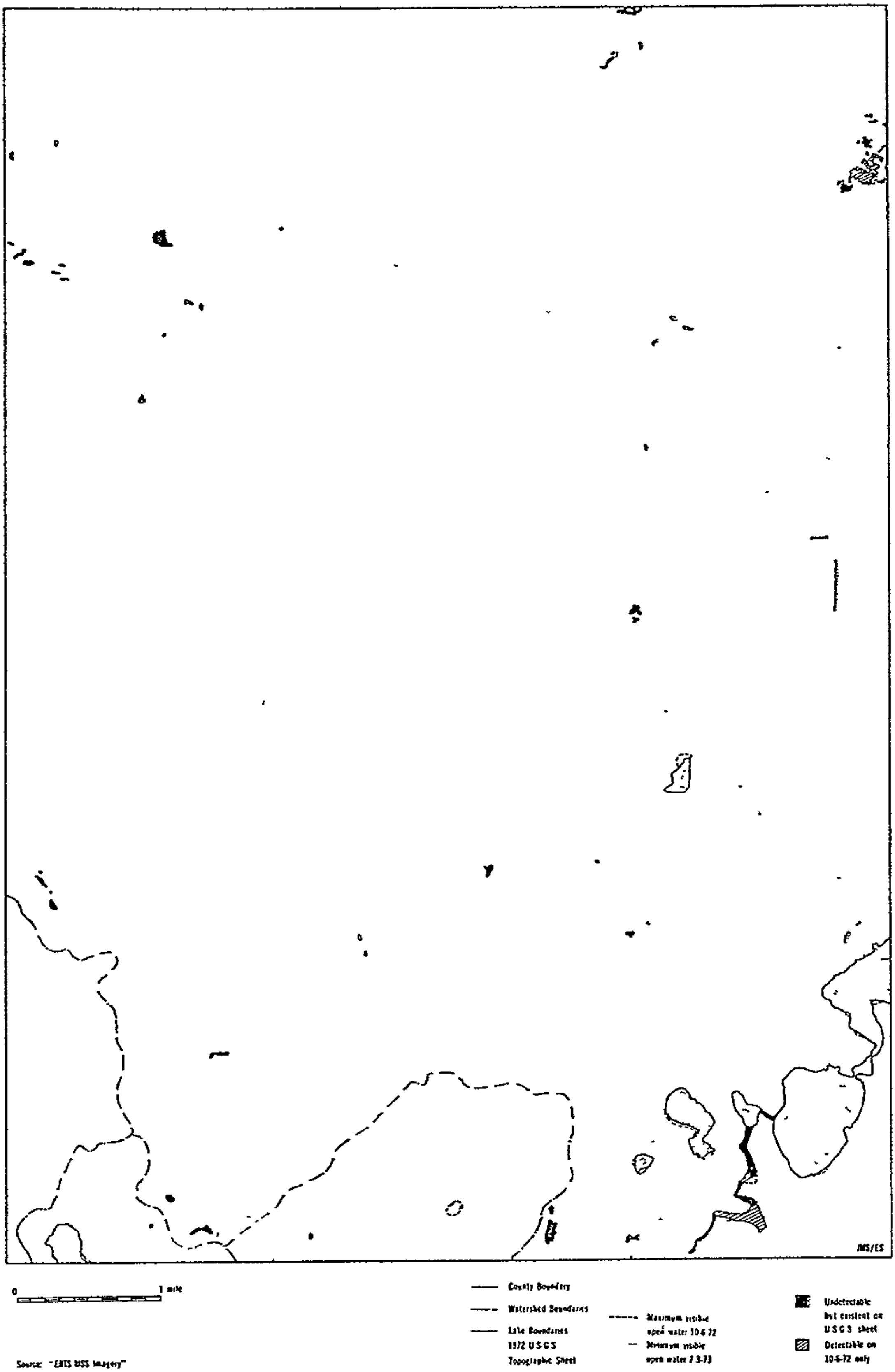
CHANGES OF VISIBLE OPEN WATER



Source "ERTS MSS Imagery"

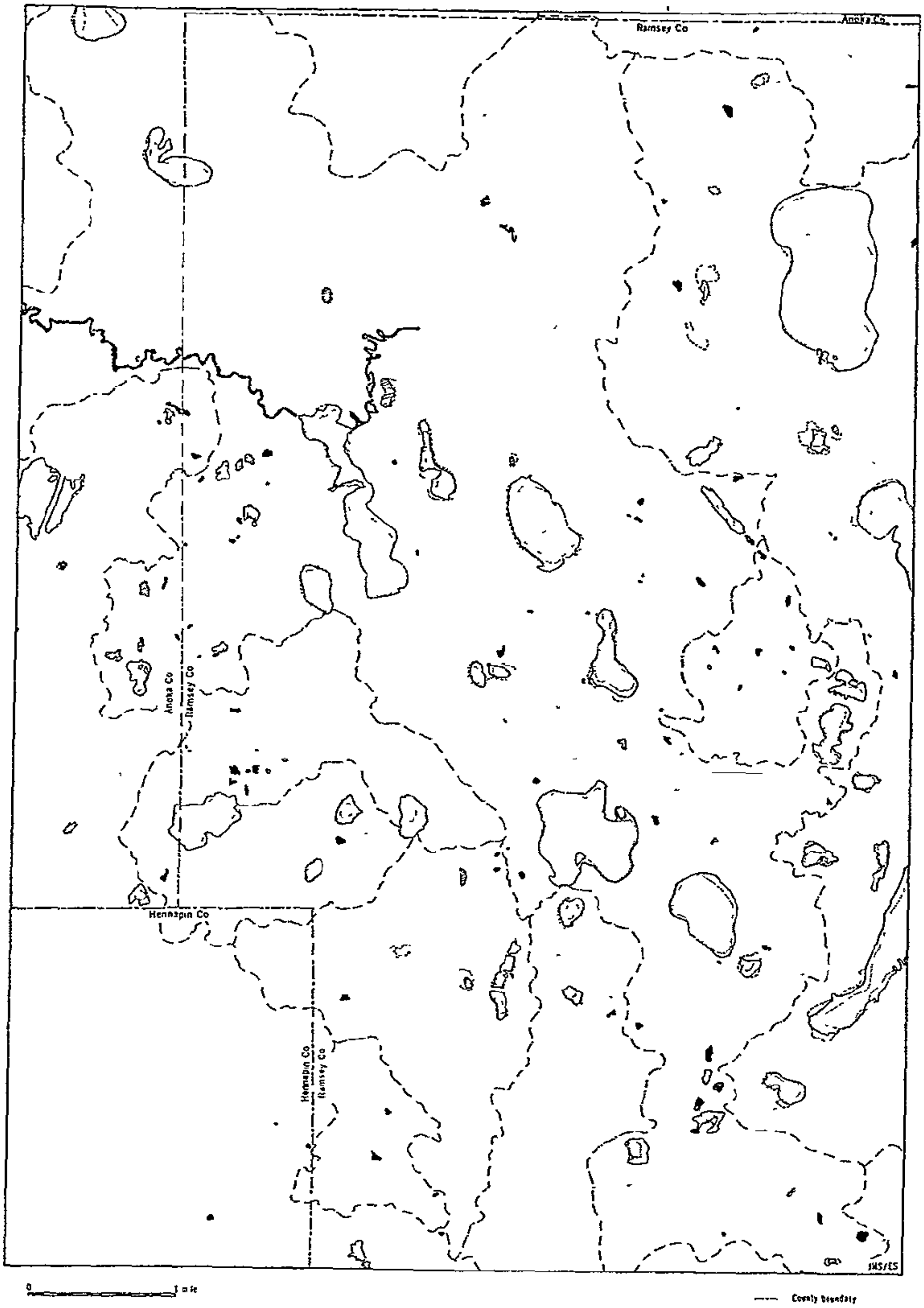
CIRCLE PINES QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



NEW BRIGHTON QUADRANGLE, MINN

VISIBLE LAKE CHANGES



Source: ERTS satellite photographs

County boundary

Lake boundaries 1972 U.S.G.S. Topographic Sheet

Undetectable but existent on U.S.G.S. sheet

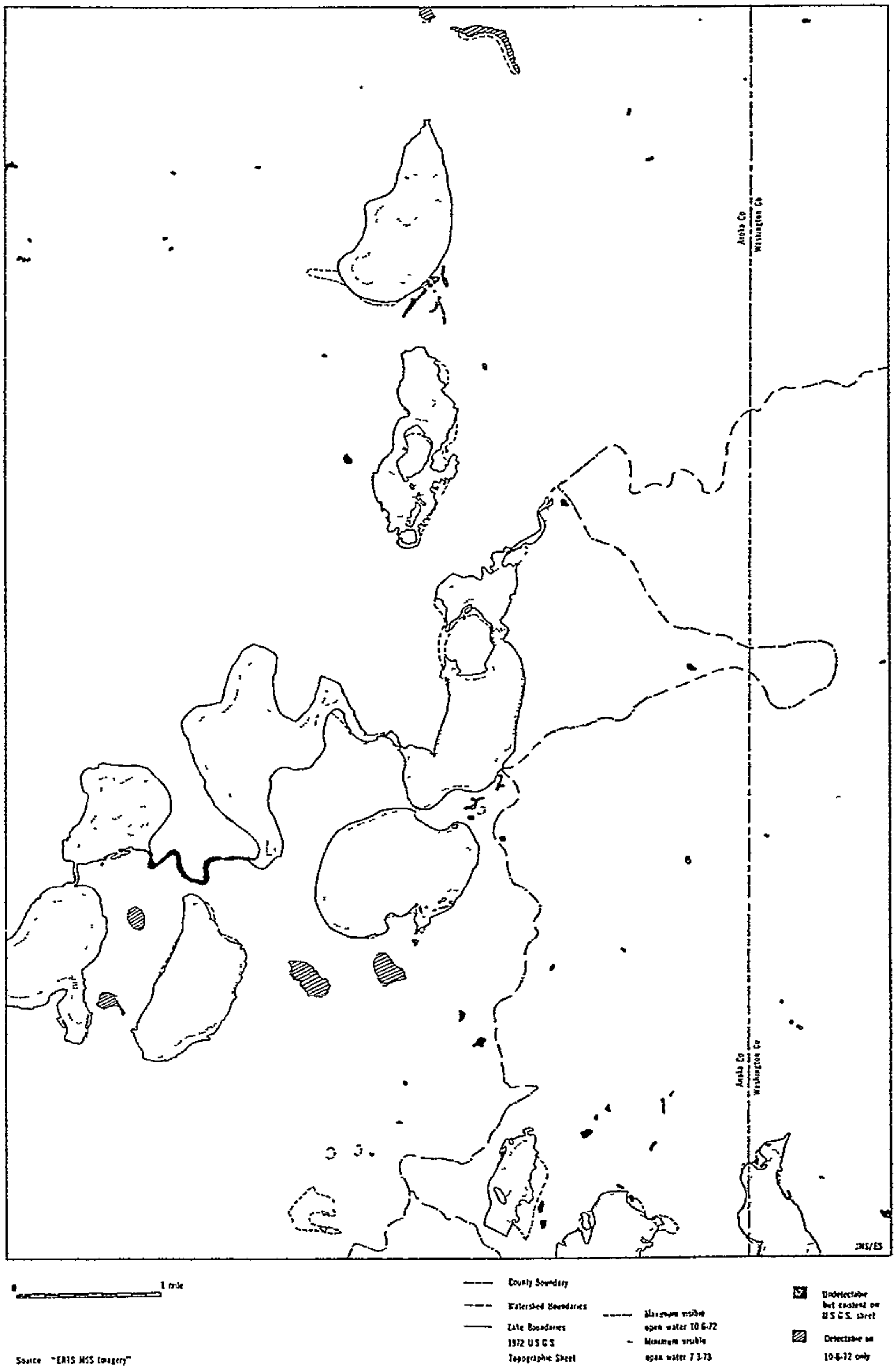
Detectable on 10-6-72 only

Maximum visible change 10-6-72

Minimum visible open water 7-3-73

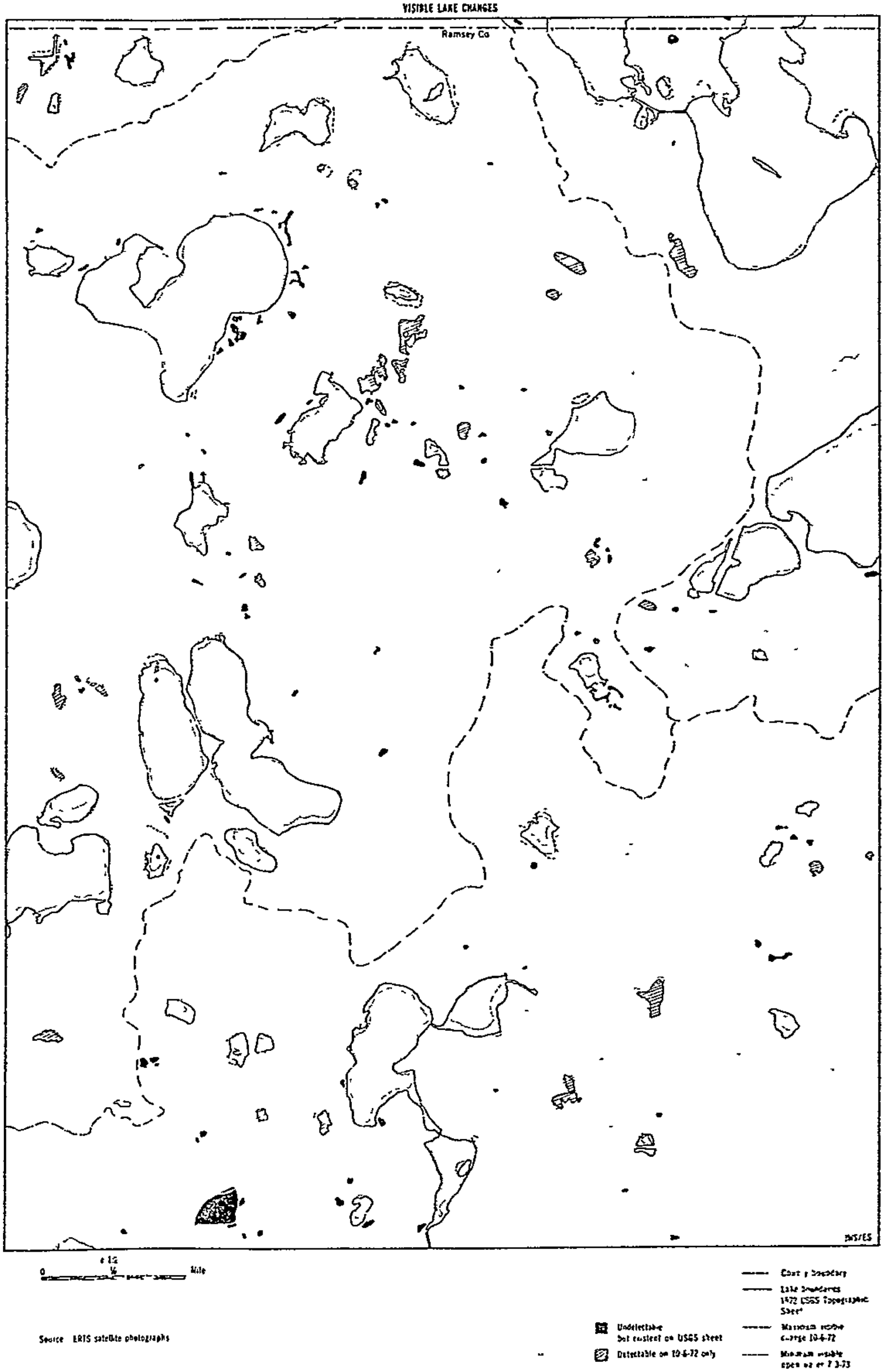
CENTERVILLE QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



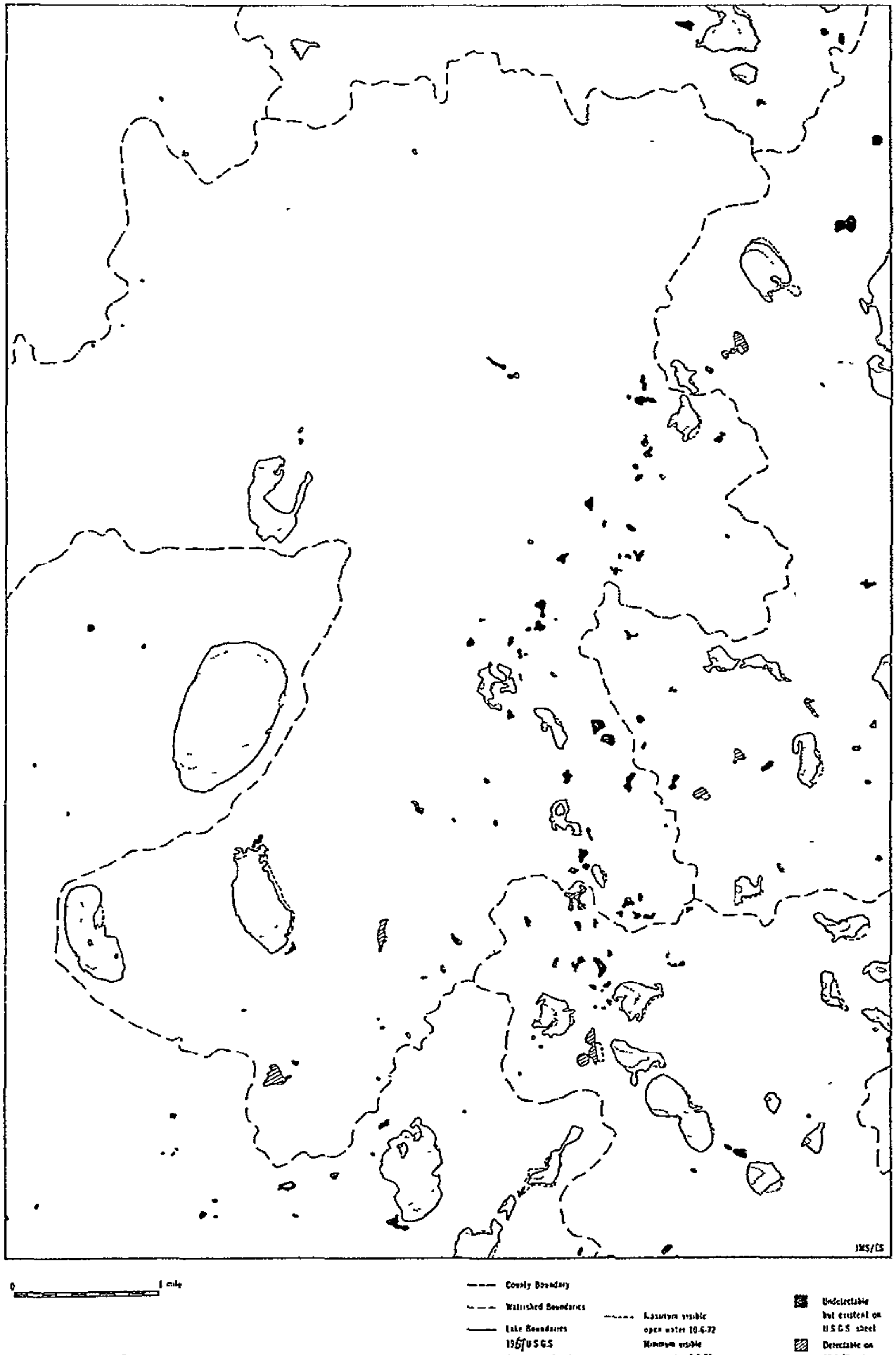
WHITE BEAR LAKE WEST, MINN

VISIBLE LAKE CHANGES



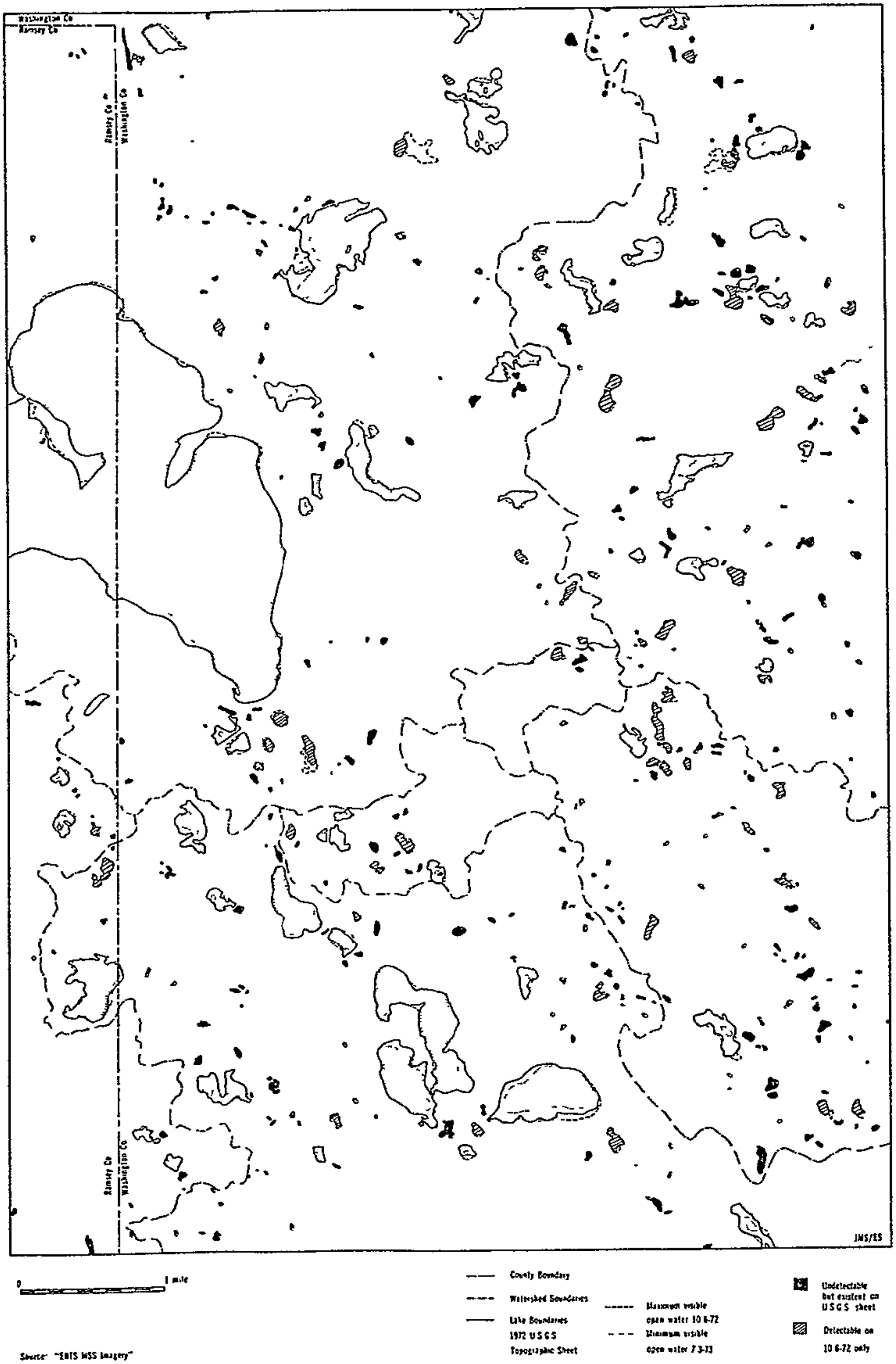
HUGO QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



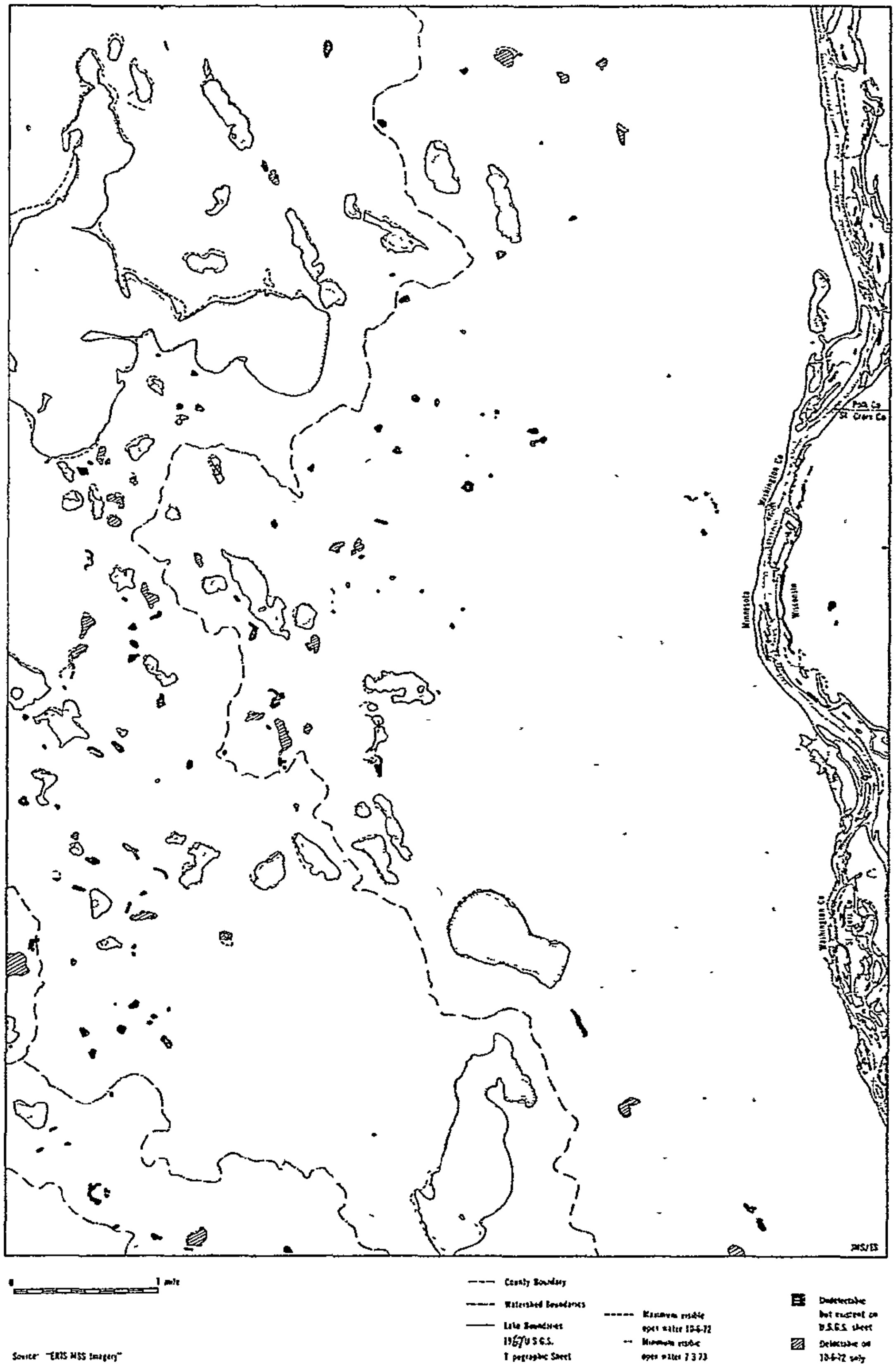
WHITE BEAR LAKE E QUADRANGLE, MINN.

CHANGES OF VISIBLE OPEN WATER



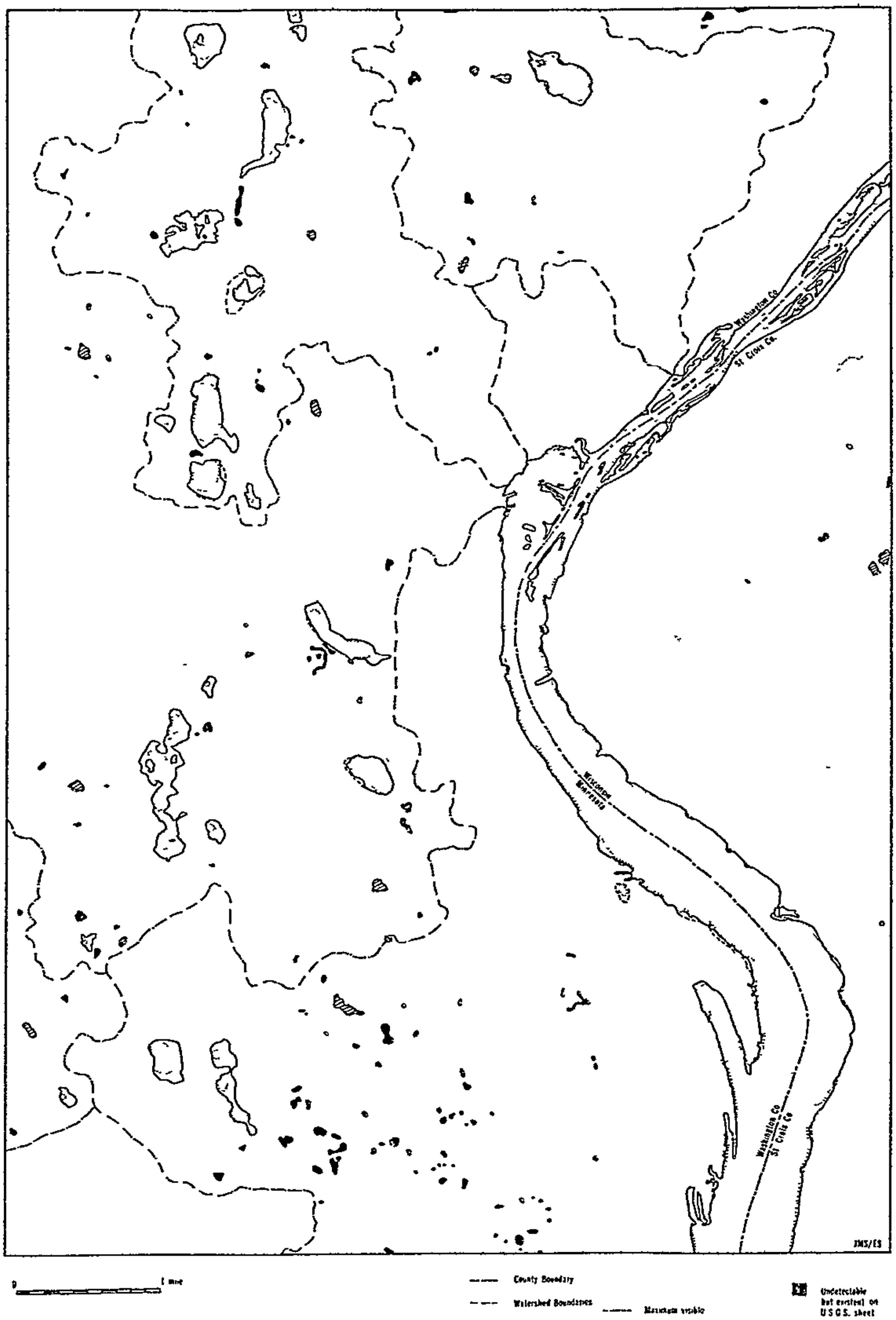
MARINE ON ST CROIX QUADRANGLE, MINN -WIS

CHANGES OF VISIBLE OPEN WATER



STILLWATER QUADRANGLE, MINN

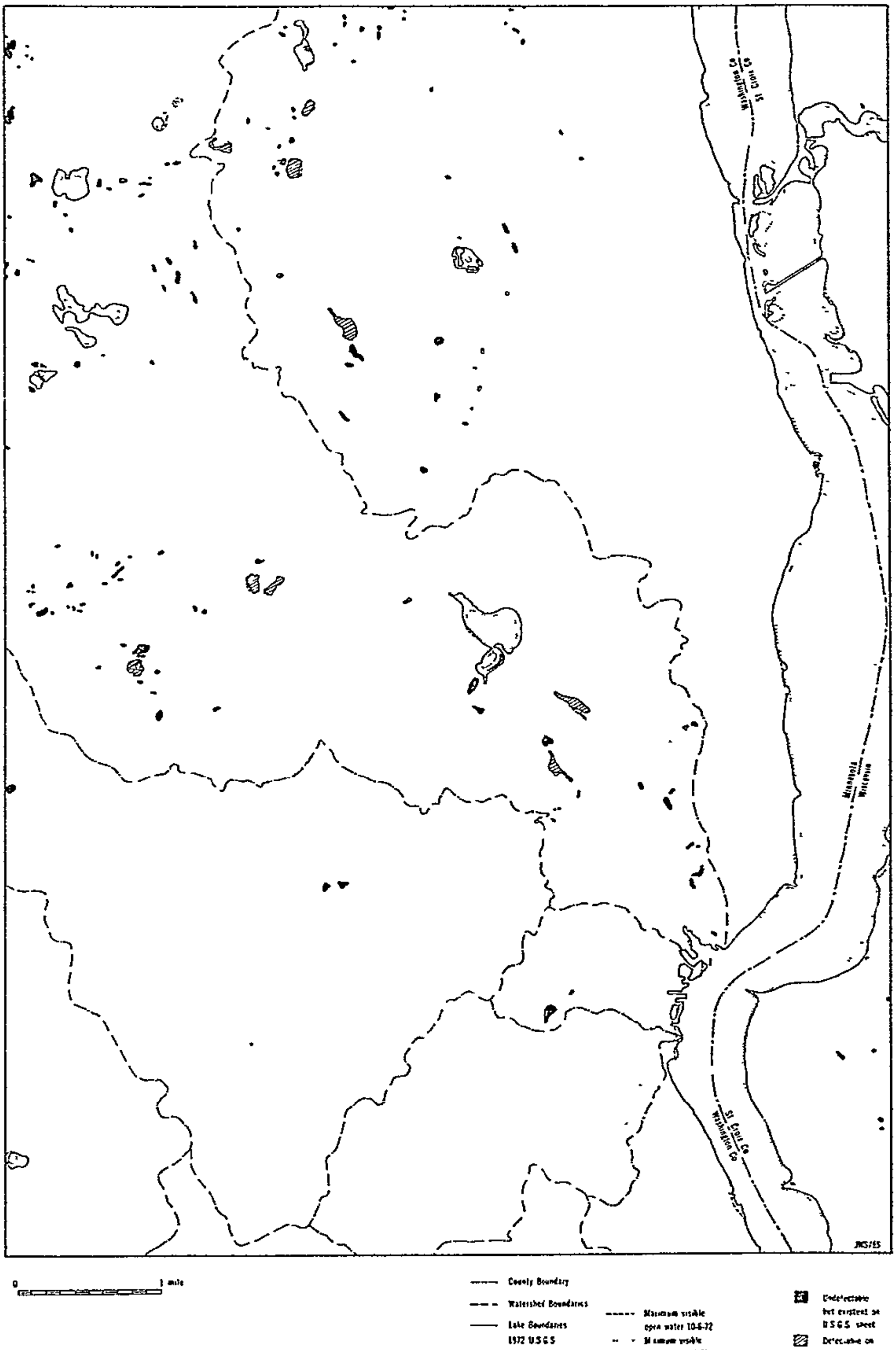
CHANGES OF VISIBLE OPEN WATER



Source: "ERTS MSS Imagery"

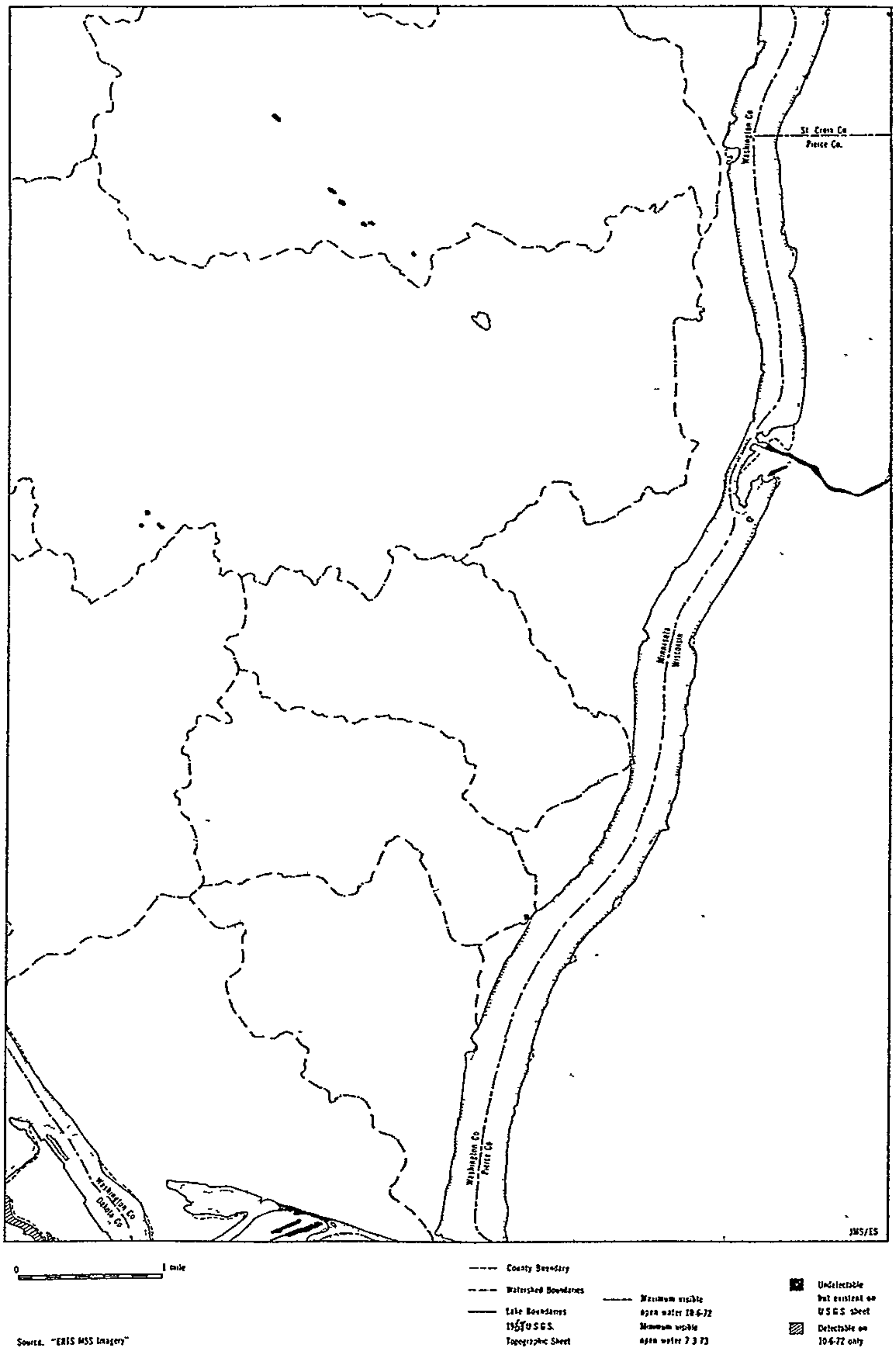
HUDSON QUADRANGLE, MINN -WIS.

CHANGES OF VISIBLE OPEN WATER



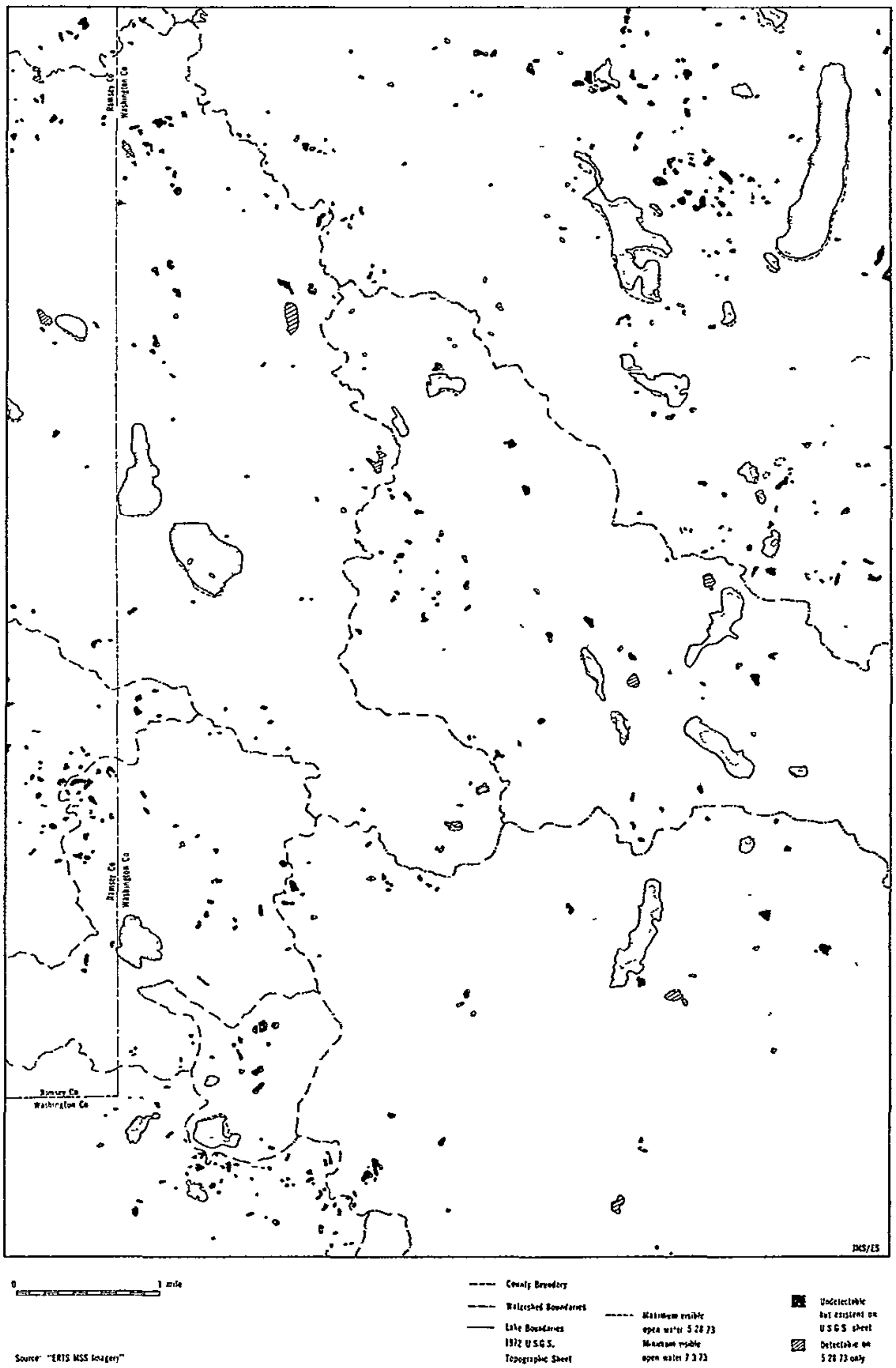
PRESCOTT QUADRANGLE, MINN -WIS

CHANGES OF VISIBLE OPEN WATER



LAKE ELMO QUADRANGLE, MINN

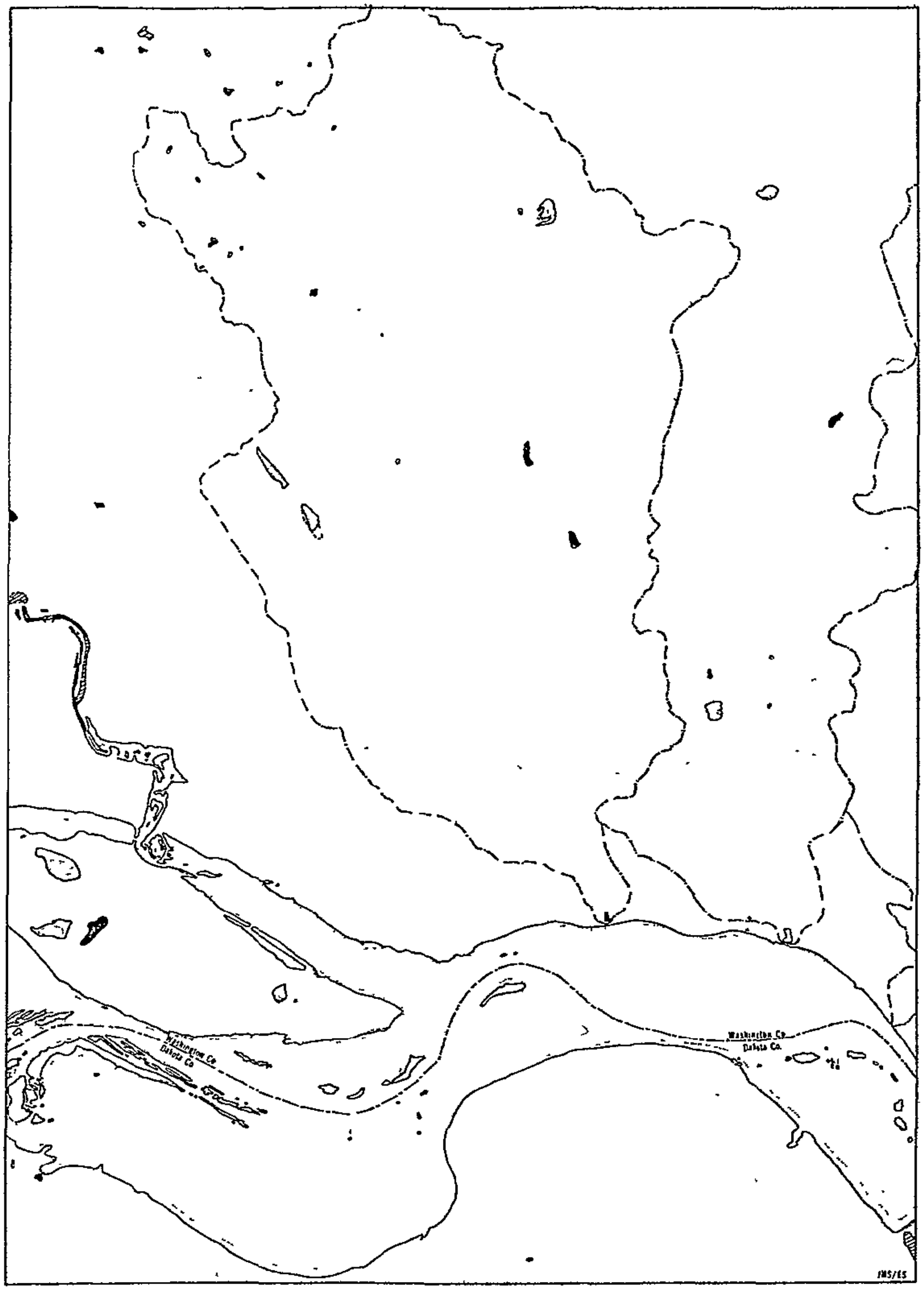
CHANGES OF VISIBLE OPEN WATER



Source: "ERTS MSS Imagery"

ST PAUL PARK QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



0 — 1 mile

County Boundary

Watershed Boundaries

Lake Boundaries 1972 U.S.G.S. Topographic Sheet

Maximum visible open water 10-6-72

Minimum visible open water 7-3-73

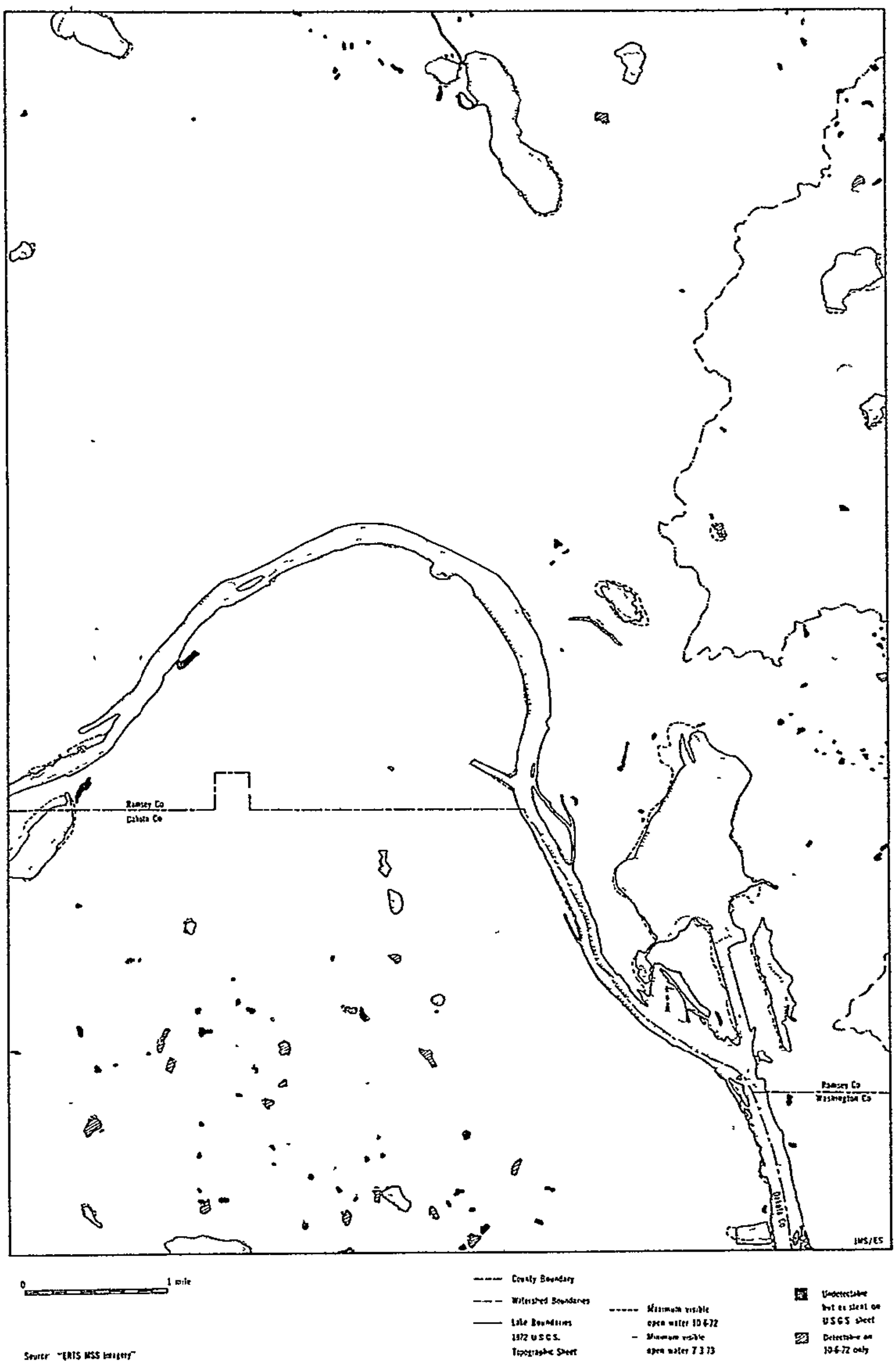
Undetectable but existent on U.S.G.S. sheet

Detectable on 10-6-72 only

Source "ERTS MSS Imagery"

ST PAUL EAST QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



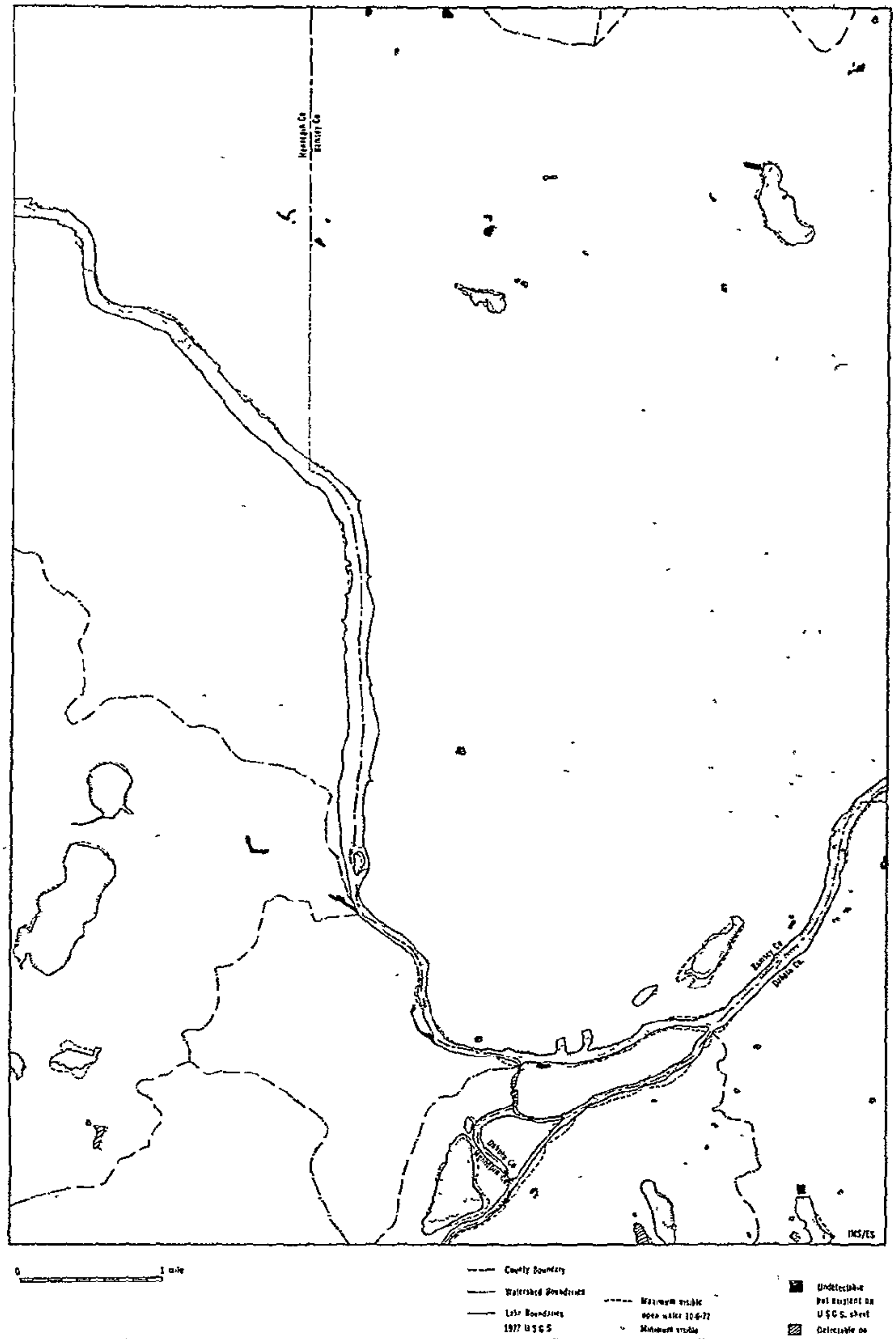
INVER GROVE HEIGHTS QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER

Source: "ERTS MSS Imagery"

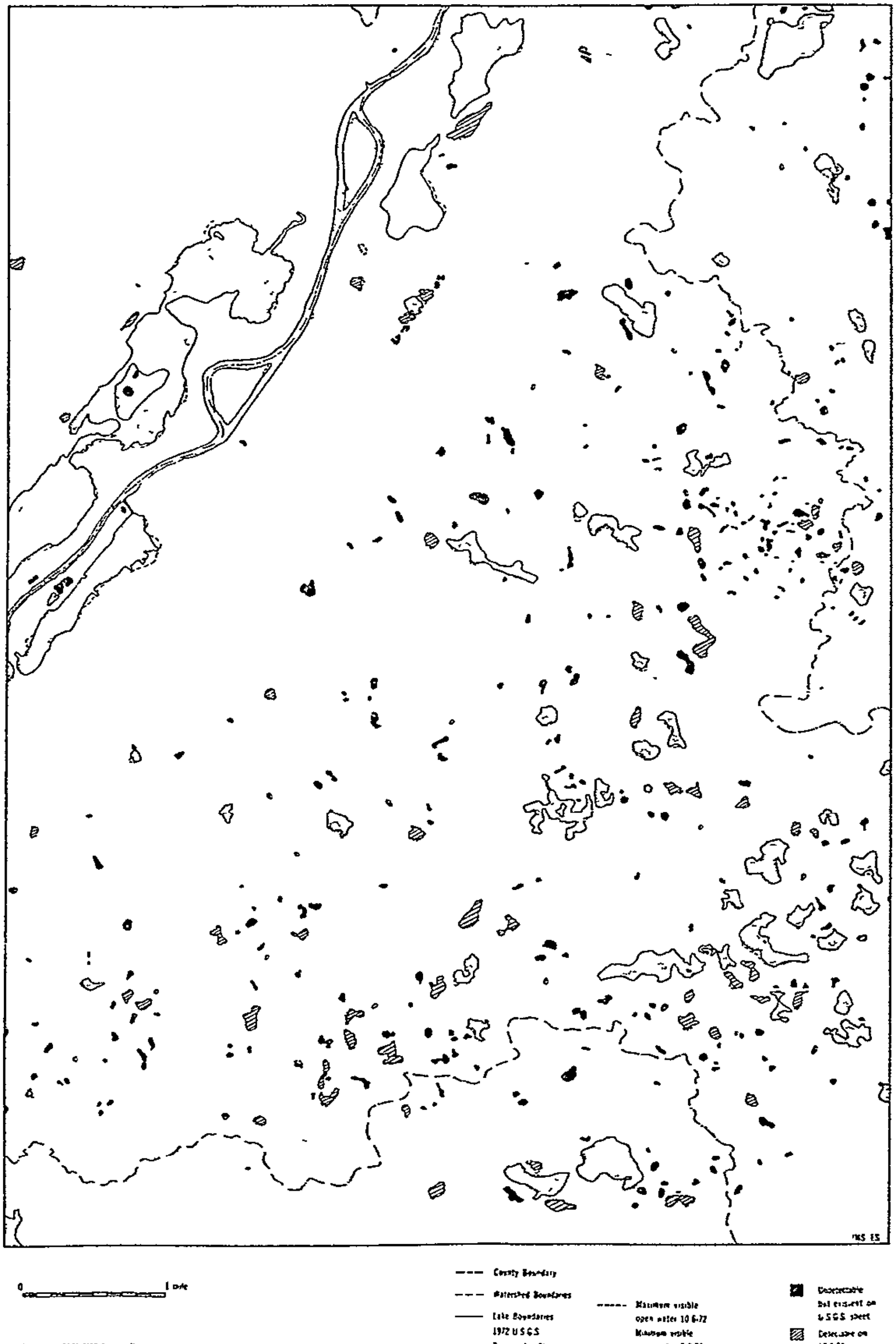
ST. PAUL WEST QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



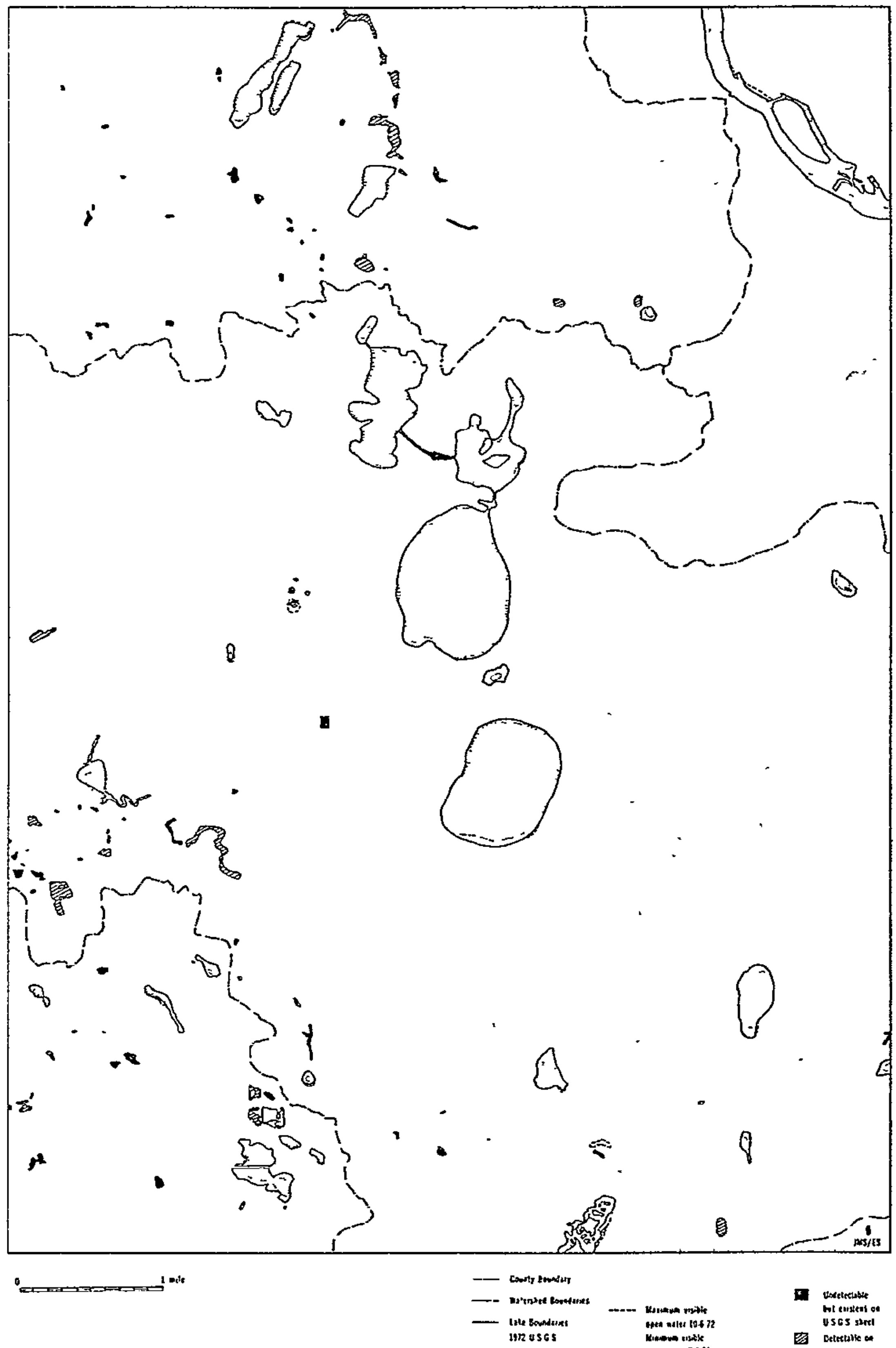
ST PAUL S W QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



MINNEAPOLIS SOUTH QUADRANGLE, MINN

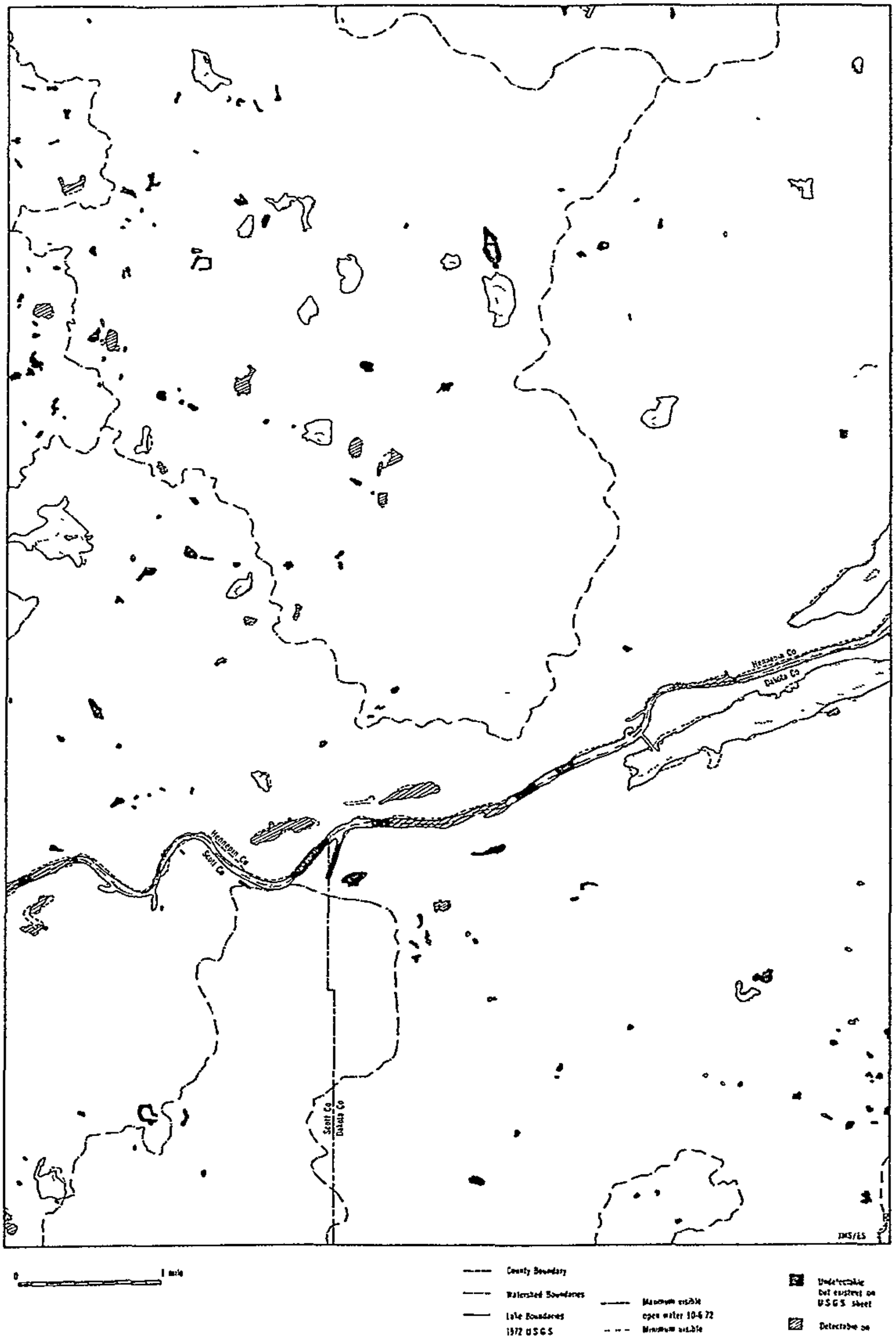
CHANGES OF VISIBLE OPEN WATER



Source "ERTS MSS Imagery"

BLOOMINGTON QUADRANGLE, MINN

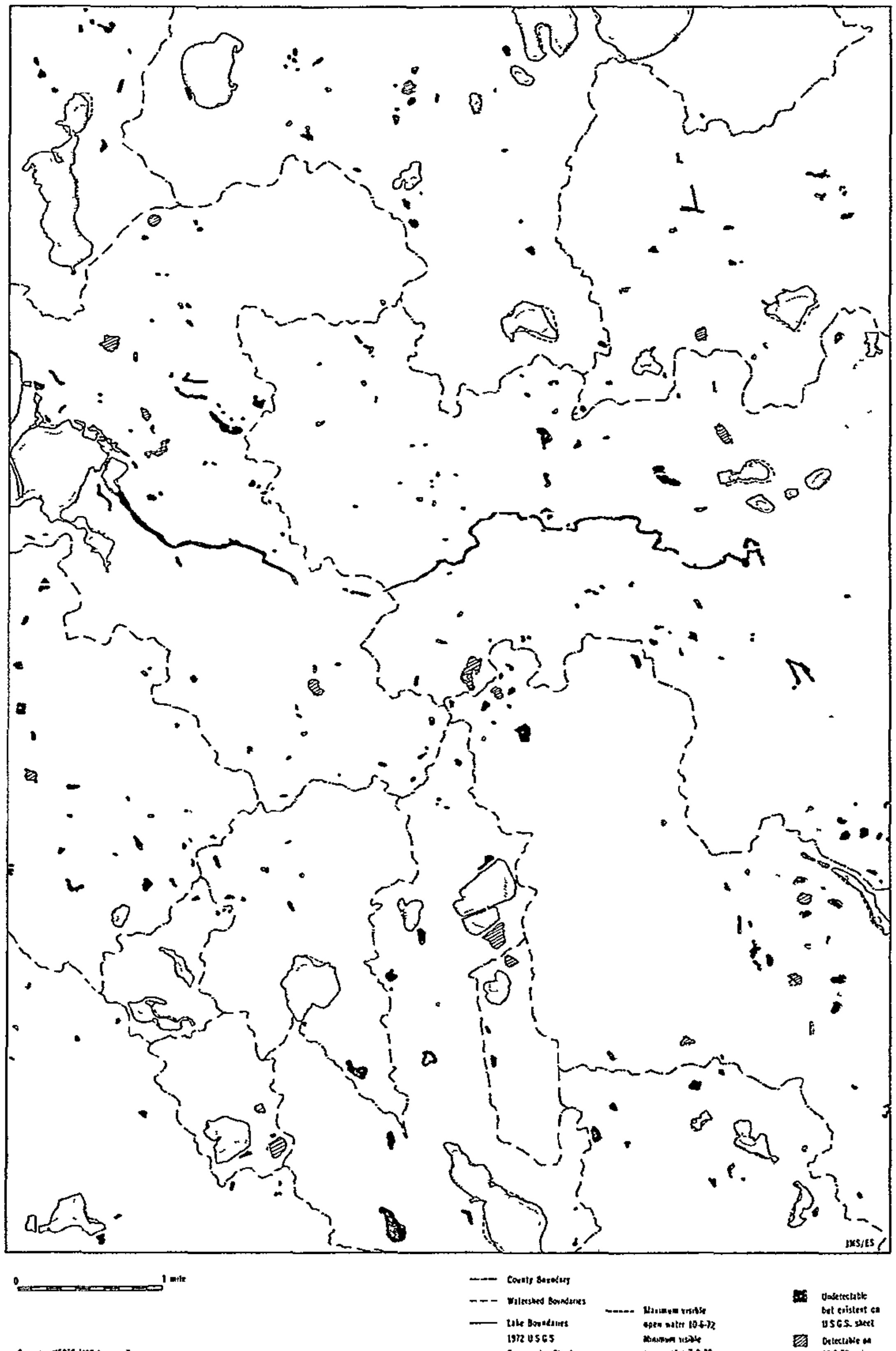
CHANGES OF VISIBLE OPEN WATER



Source "ERTS MSS Imagery"

HOPKINS QUADRANGLE, MINN

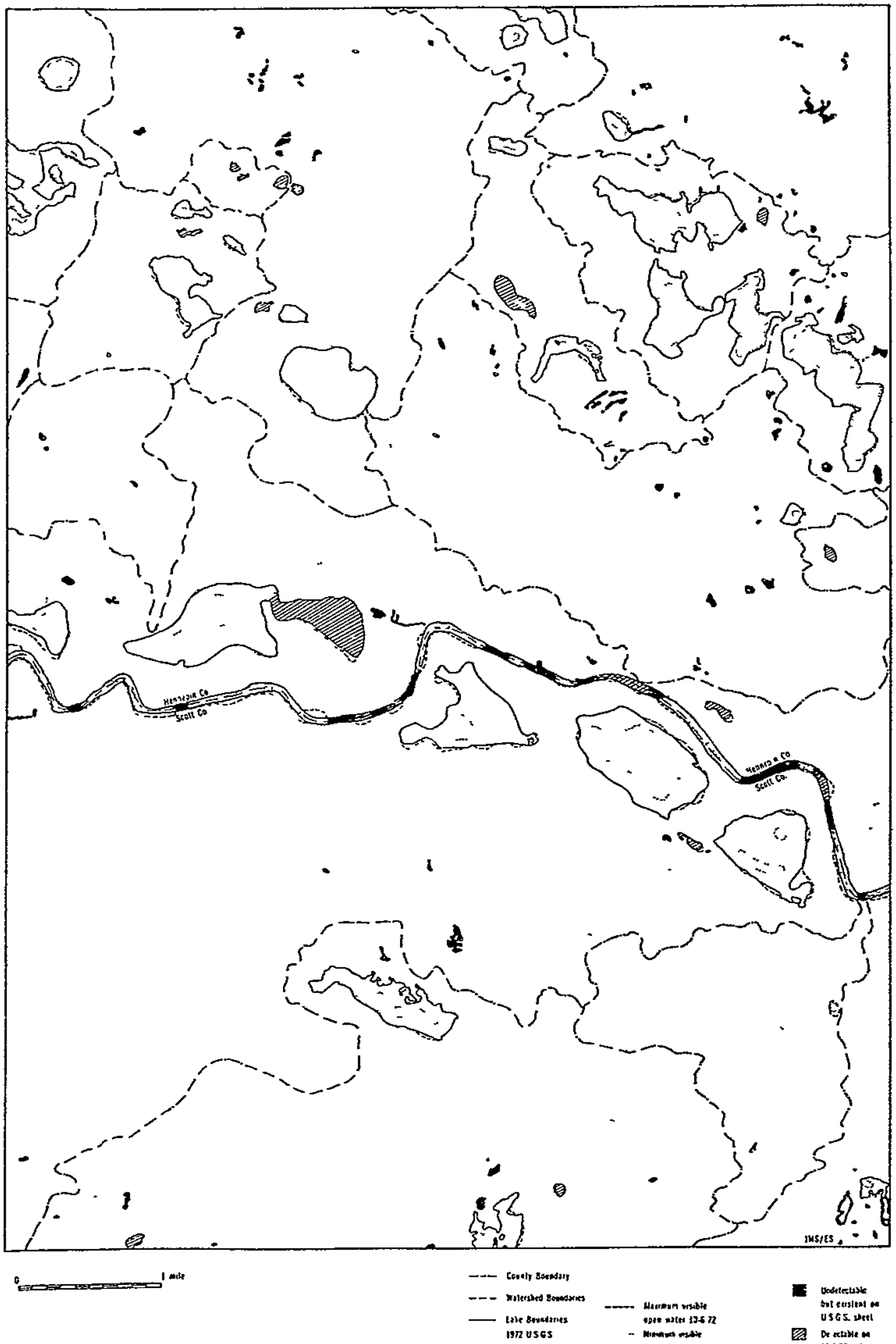
CHANGES OF VISIBLE OPEN WATER



Source: "ERTS MSS Imagery"

EDEN PRAIRIE QUADRANGLE, MINN

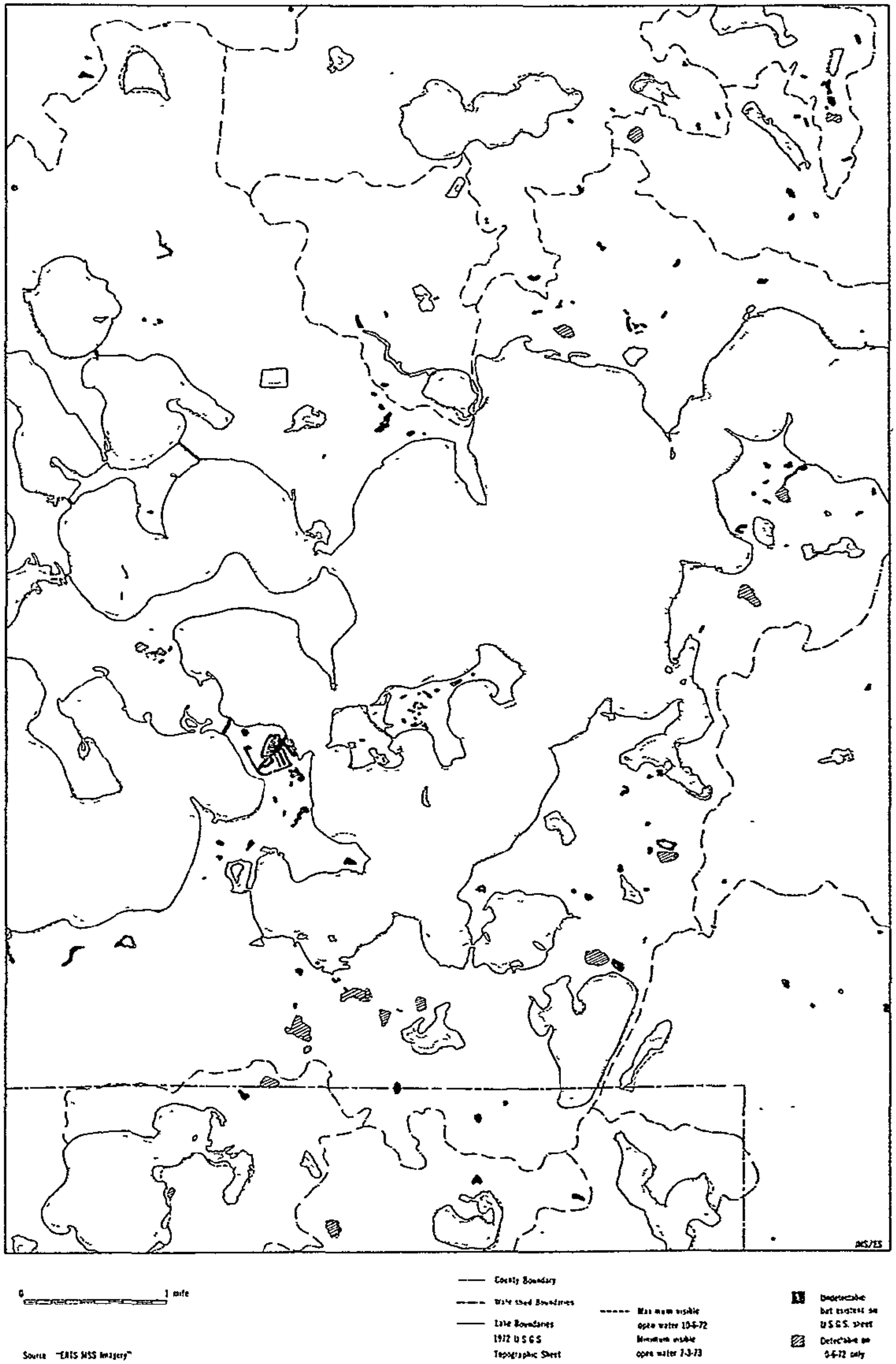
CHANGES OF VISIBLE OPEN WATER



Source "ERTS MSS Imagery"

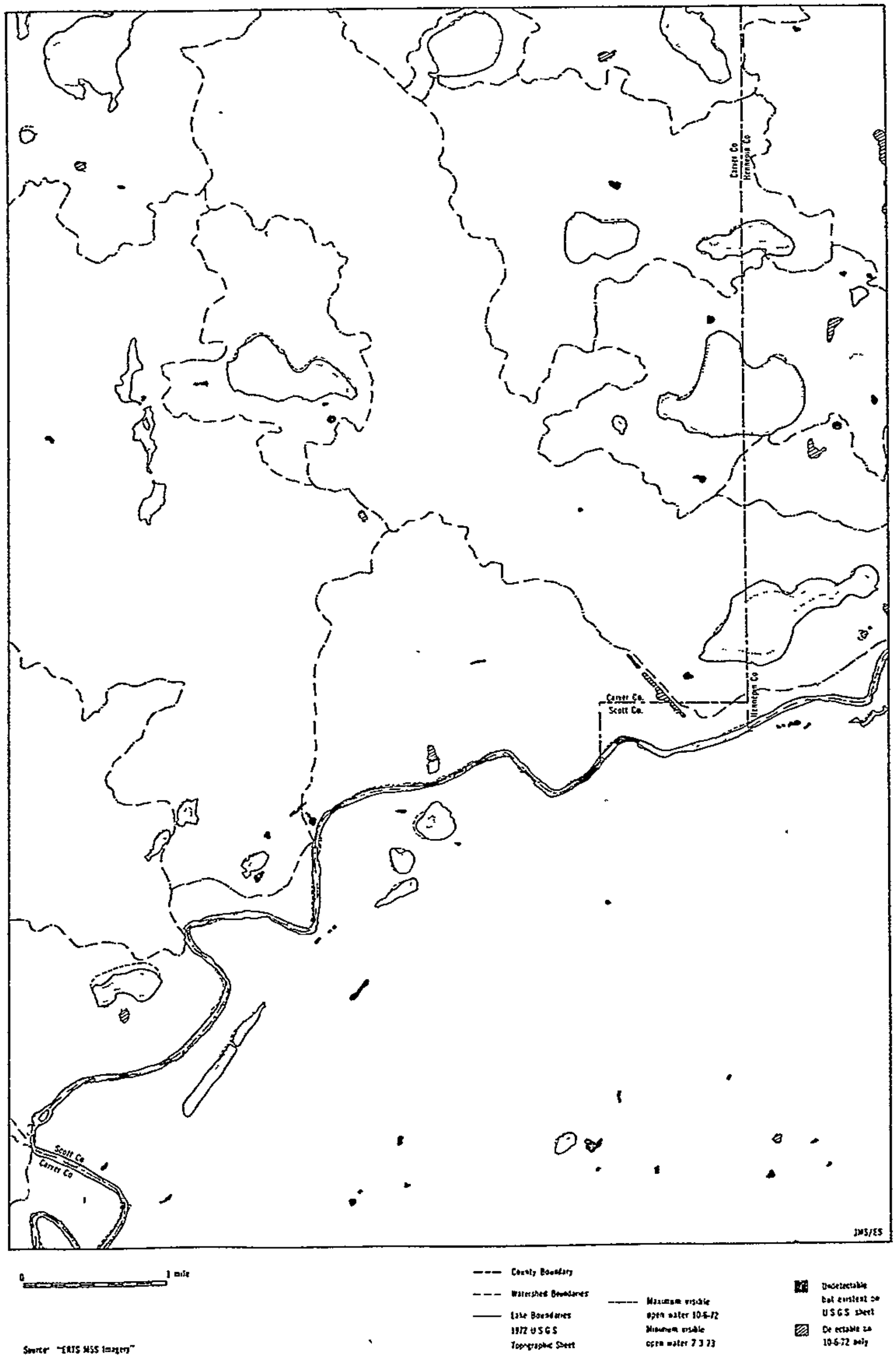
EXCELSIOR QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



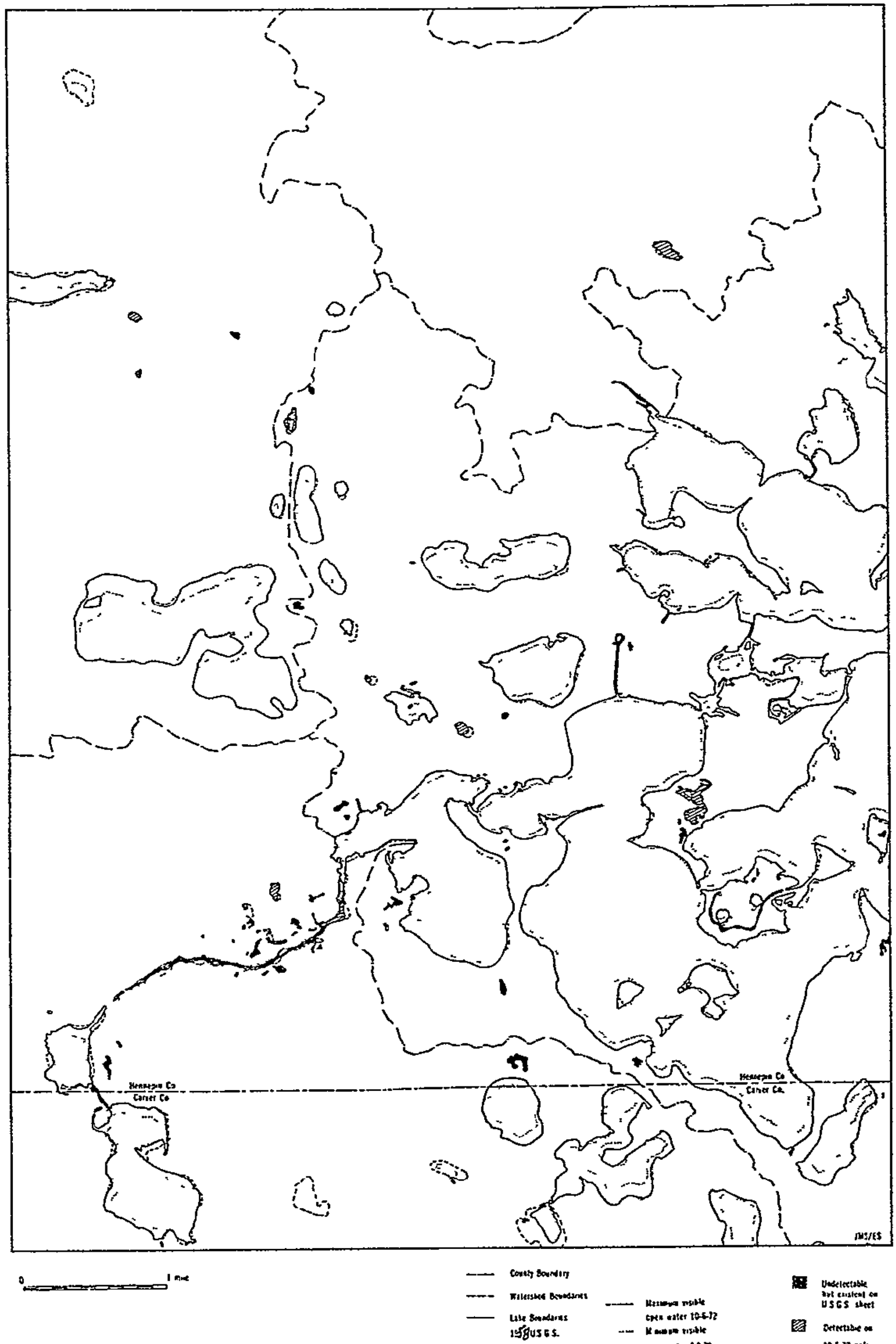
SHAKOPEE QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



MOUND QUADRANGLE, MINN

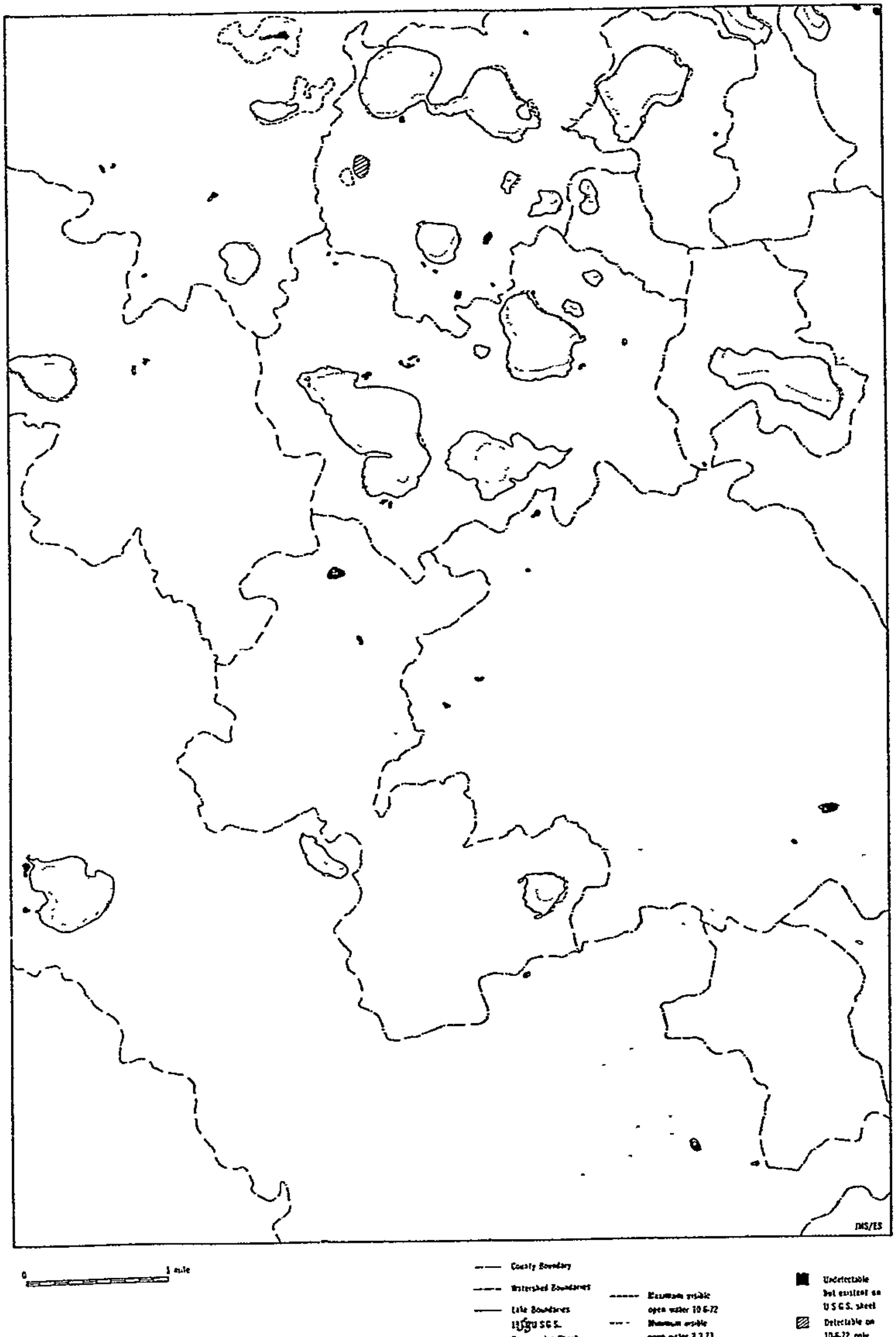
CHANGES OF VISIBLE OPEN WATER



Source "ERTS MSS Imagery"

VICTORIA QUADRANGLE, MINN.

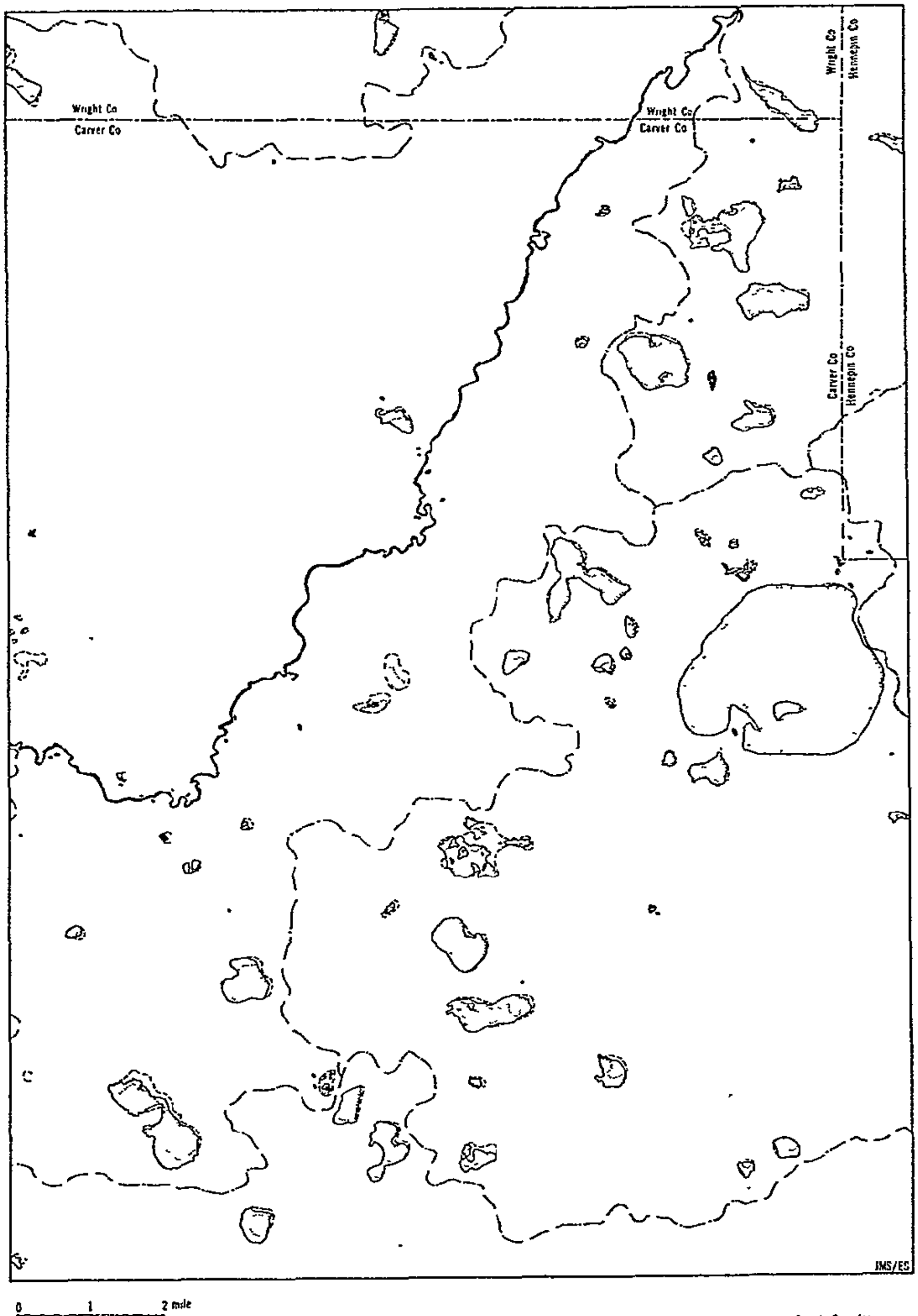
CHANGES OF VISIBLE OPEN WATER



Source: "ERTS MSS Imagery"

WACONIA QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER

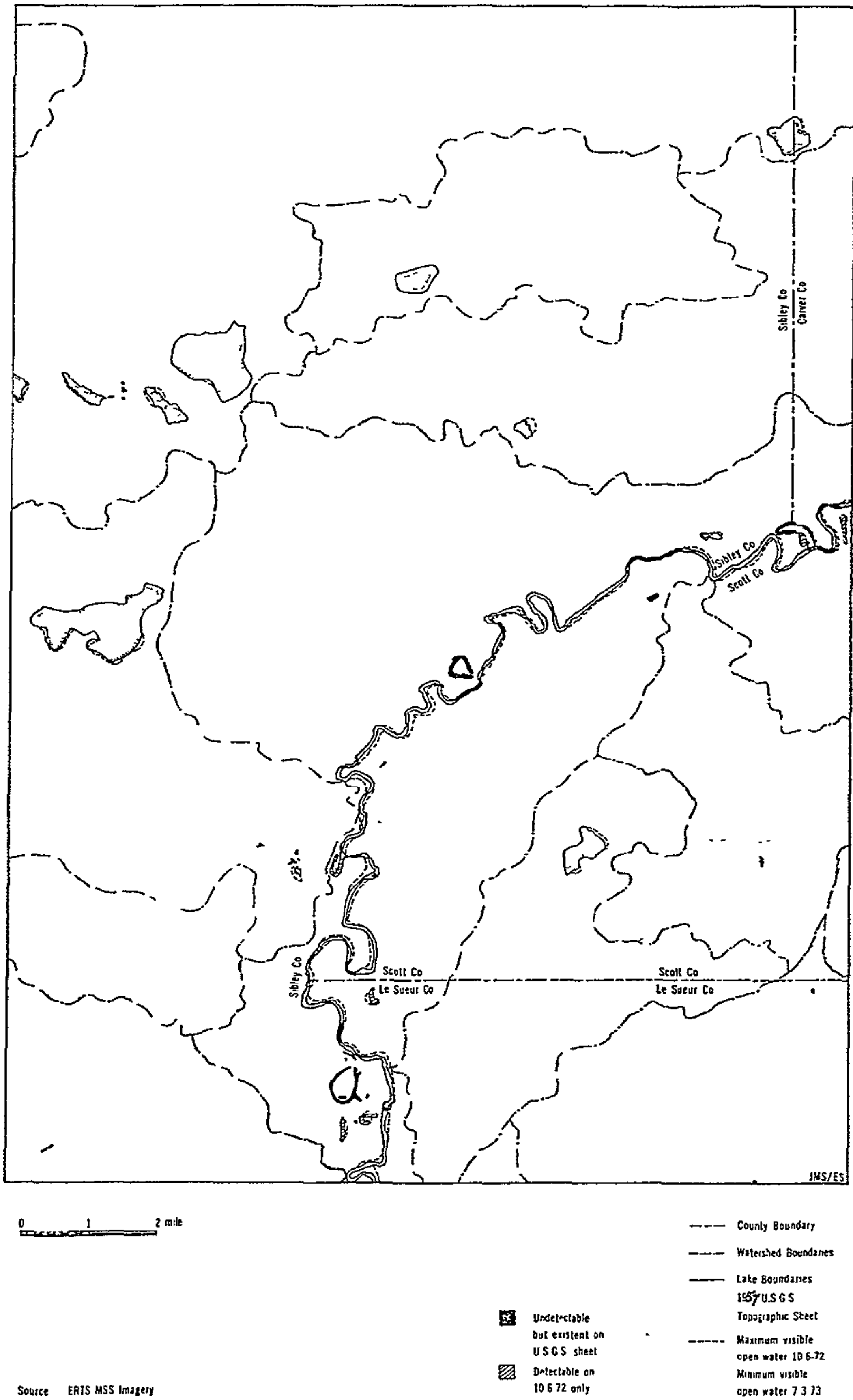


County Boundary
Watershed Boundaries
Lake Boundaries 1957 U S G S Topographic Sheet
Maximum visible open water 10-6 72
Minimum visible open water 7-3-73

Undetectable but existent on U S G.S. sheet
Detectable on 10-6 72 only

Source "ERTS MSS Imagery

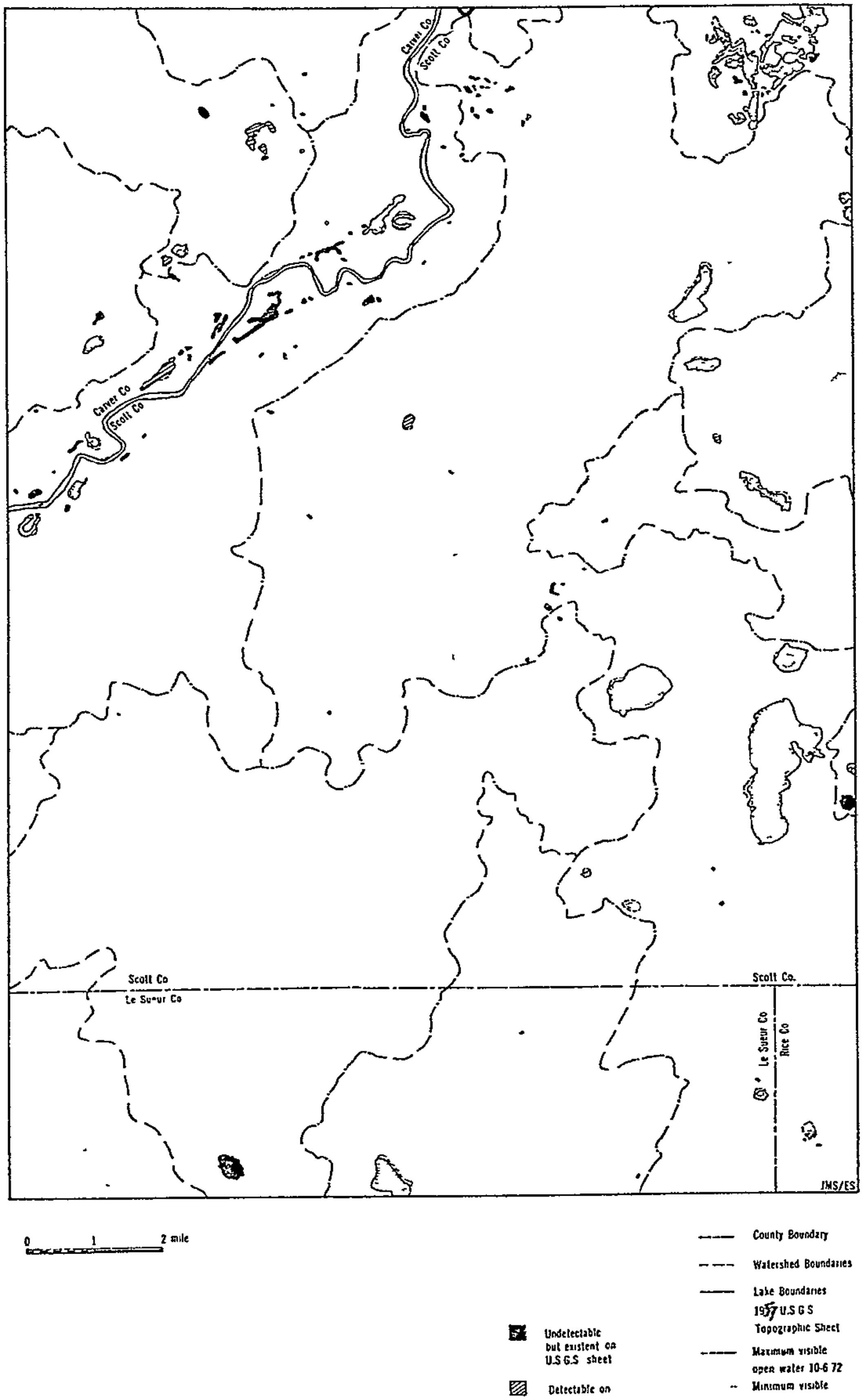
BELLE PLAINE QUADRANGLE, MINN
CHANGES OF VISIBLE OPEN WATER



Source ERTS MSS Imagery

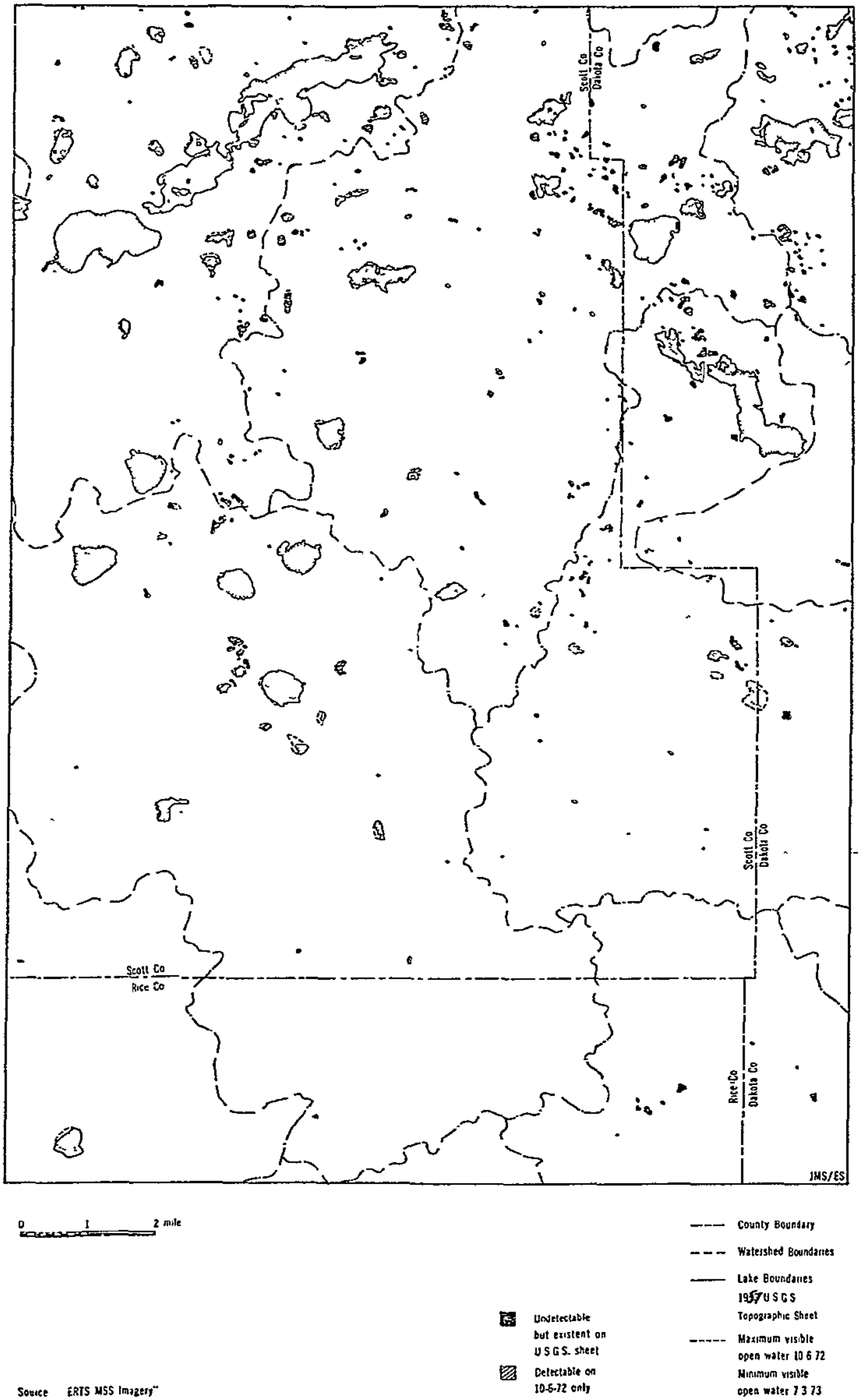
NEW PRAGUE QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



Source ERTS MSS Imagery"

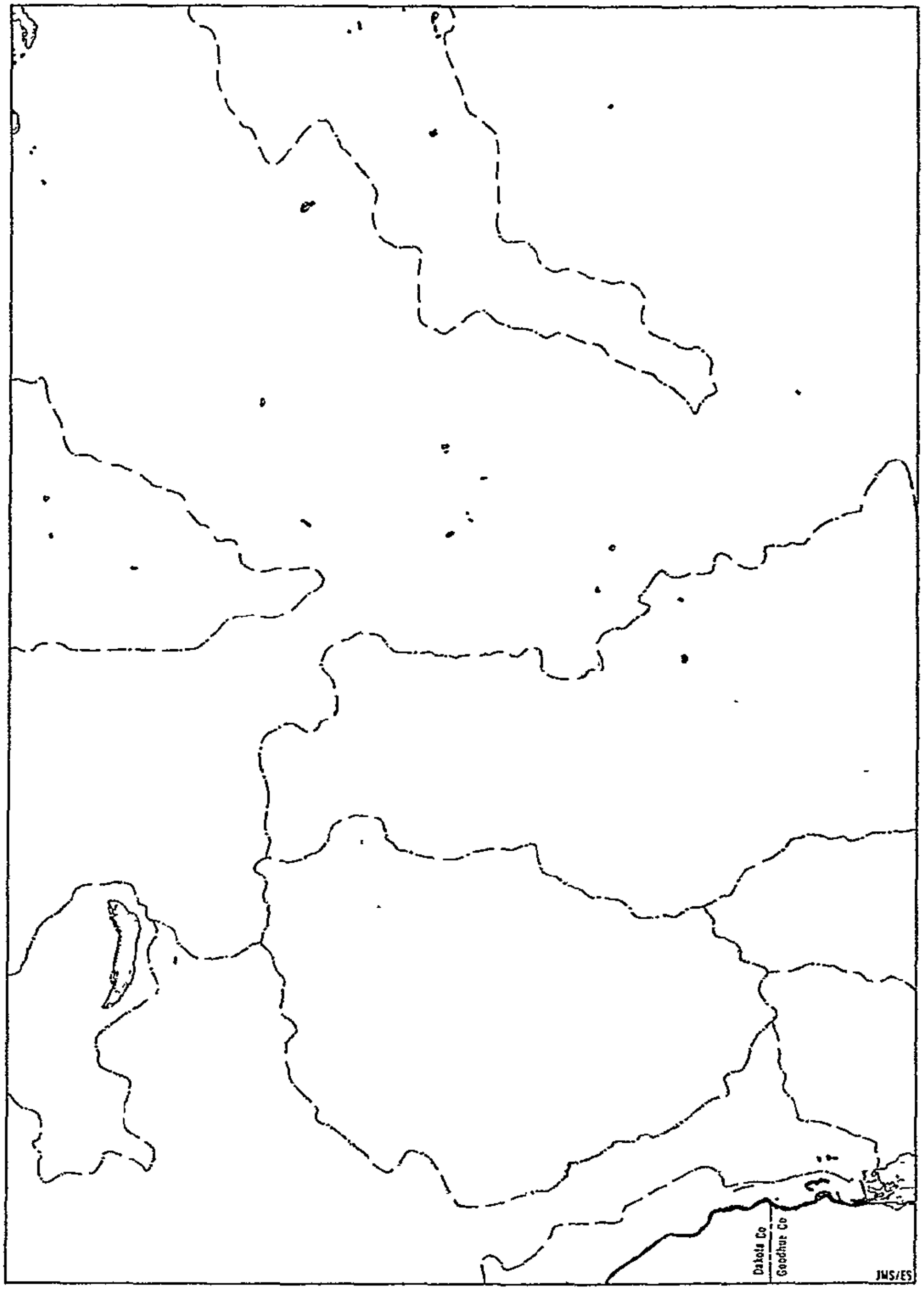
PRIOR LAKE QUADRANGLE, MINN
CHANGES OF VISIBLE OPEN WATER



Source ERTS MSS Imagery

FARMINGTON QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



0 1 2 mile

Source ERTS MSS Imagery

Undetectable but existent on USGS sheet

Detectable on 10 6 72 only

County Boundary

Watershed Boundaries

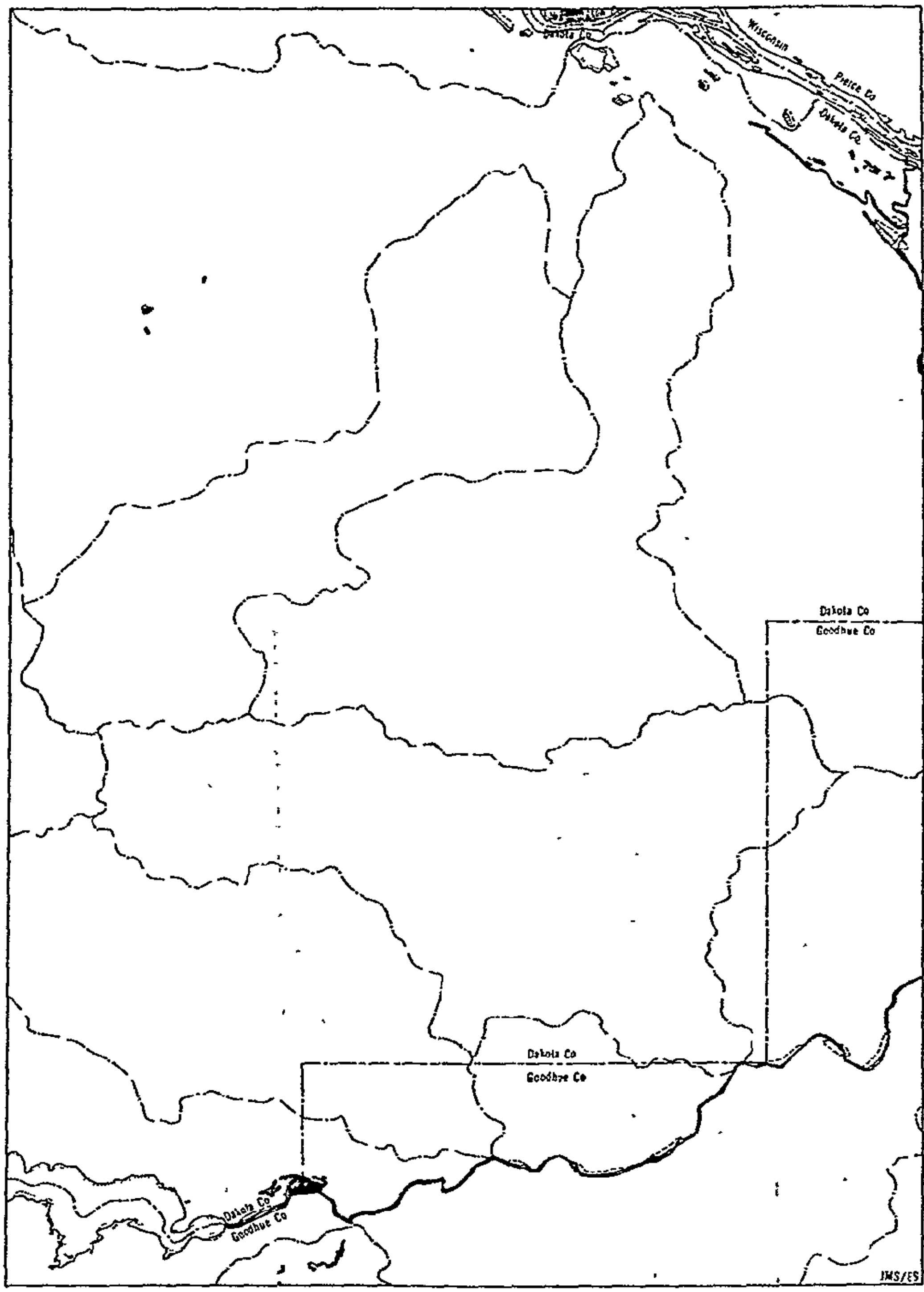
Lake Boundaries 1957 USGS Topographic Sheet

Maximum visible open water 10-6-72

Minimum visible open water 7 3-73

HASTINGS QUADRANGLE, MINN -WIS

CHANGES OF VISIBLE OPEN WATER



0 1 2 mile

Undetectable but existent on USGS sheet

Detectable on 10-6-72 only

County Boundary

Watershed Boundaries

Lake Boundaries 1957 U.S.G.S. Topographic Sheet

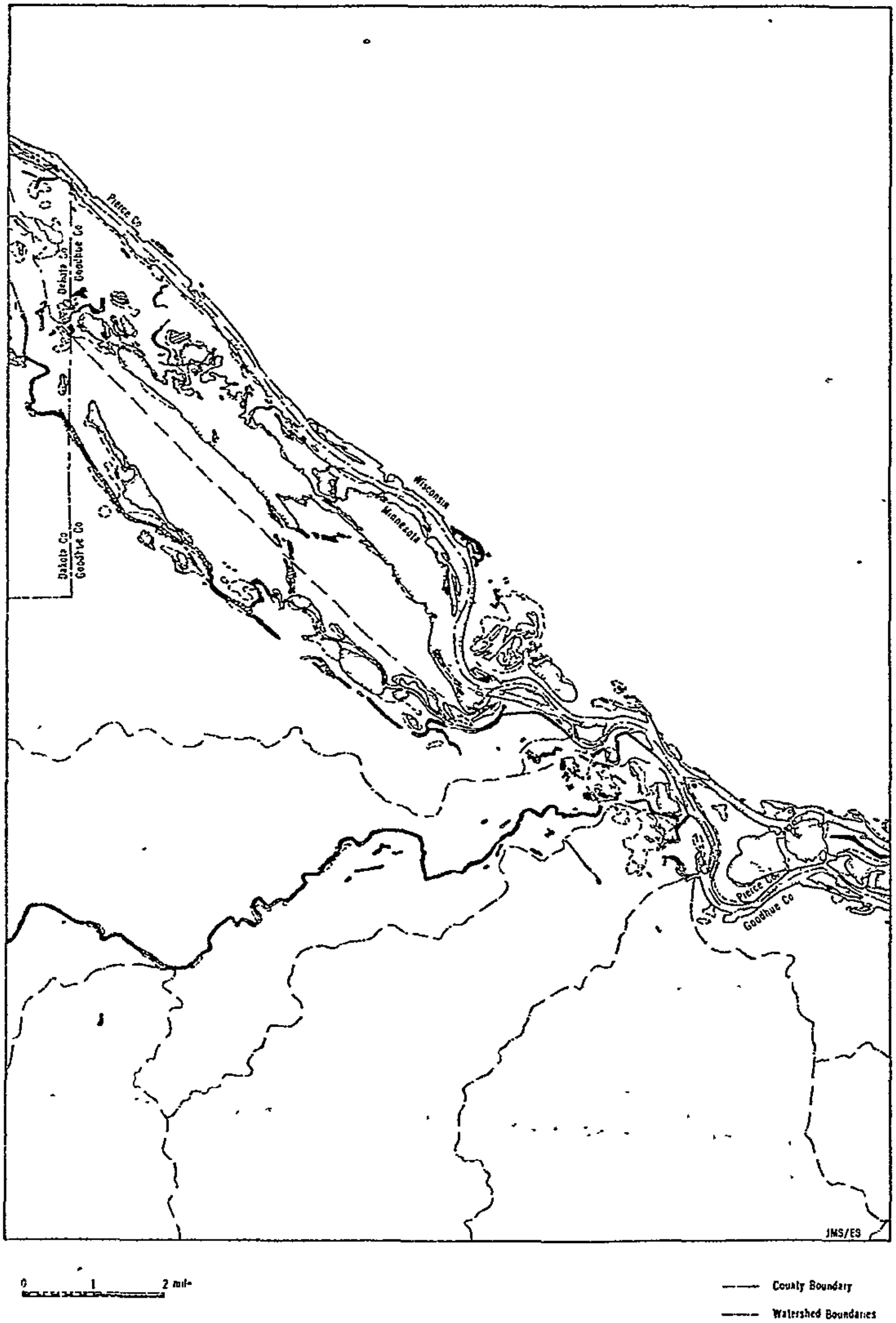
Maximum visible open water 10-6-72

Minimum visible open water 7 3 73

Source ERTS MSS Imagery

RED WING QUADRANGLE, MINN -WIS

CHANGES OF VISIBLE OPEN WATER



0 1 2 mile

—— County Boundary

—— Watershed Boundaries

—— Lake Boundaries 1952 U S G S Topographic Sheet

---- Maximum visible open water 10-6 72 Minimum visible open water 7-3 73

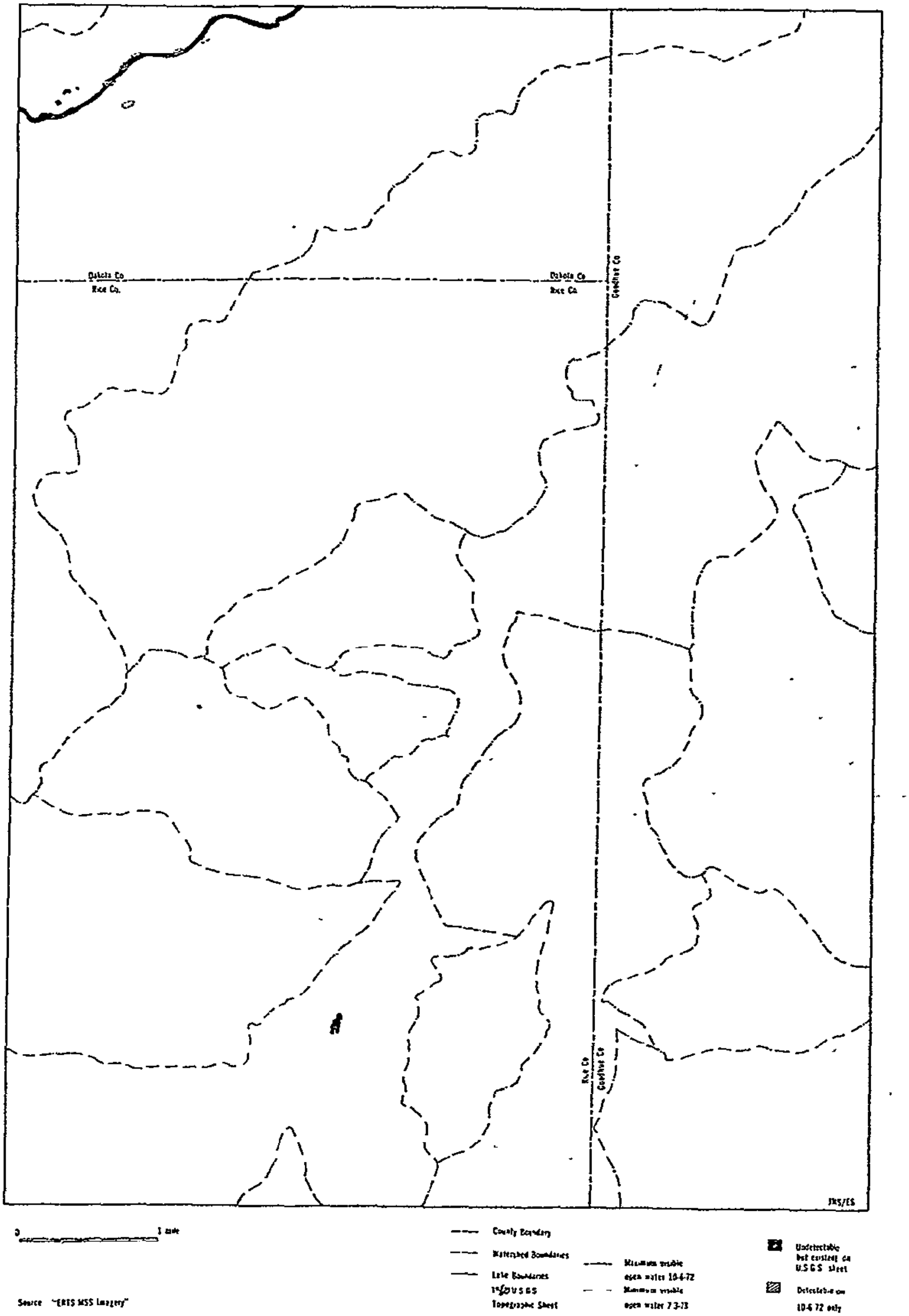
Undetectable out existent on U S G.S sheet

Detectable on 10-6-72 only

Source "ERTS MSS Imagery"

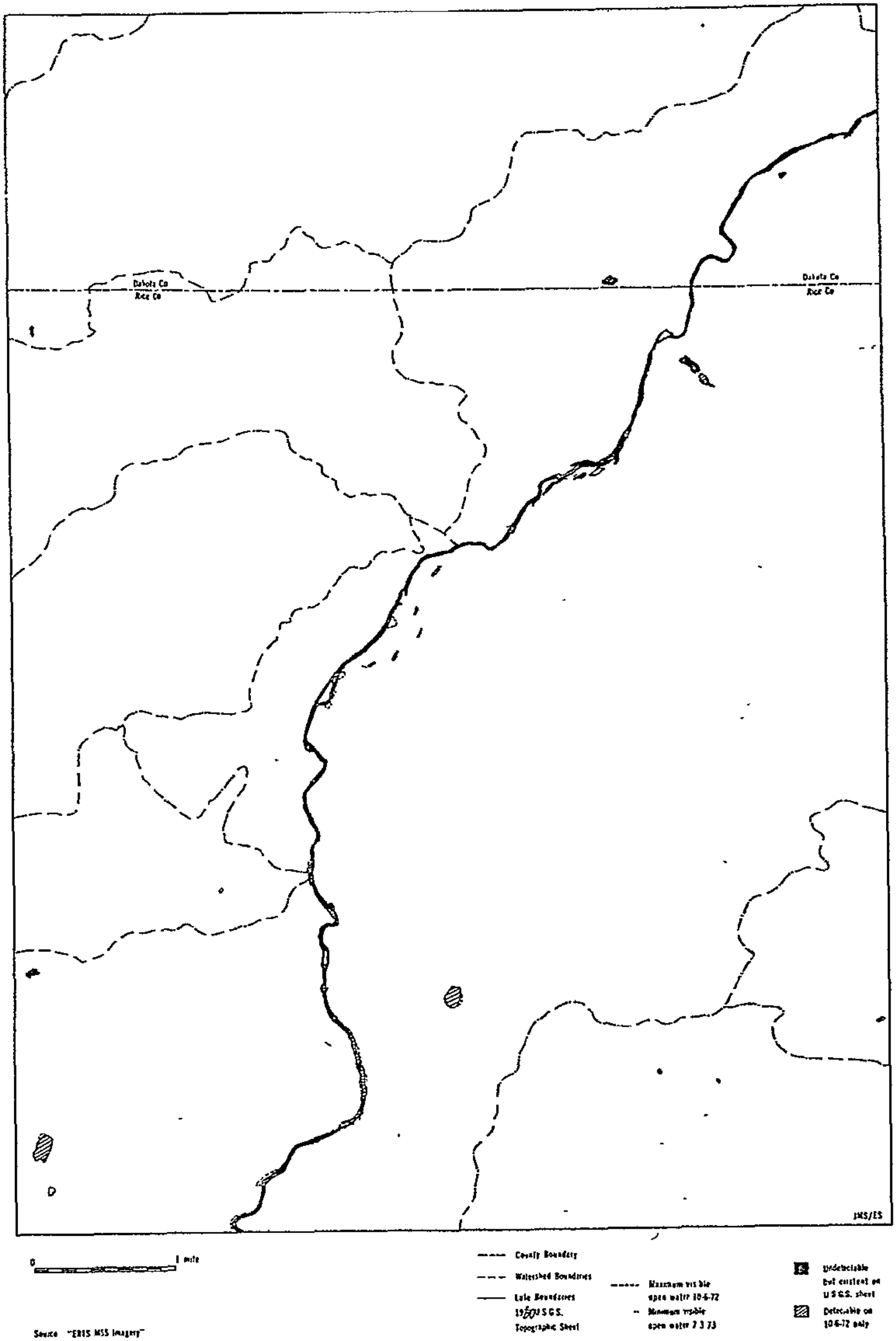
DENNISON QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



NORTHFIELD QUADRANGLE, MINN

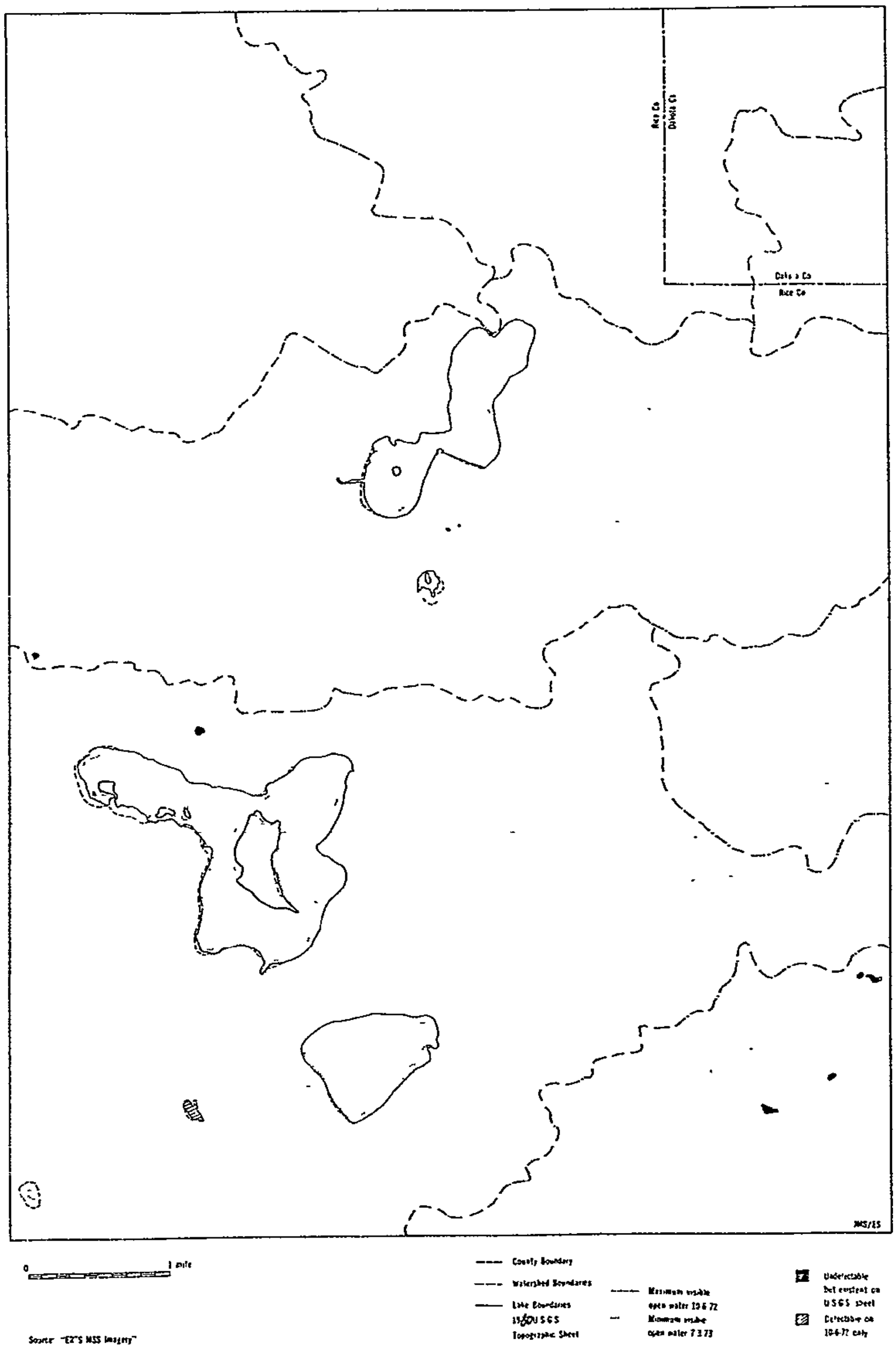
CHANGES OF VISIBLE OPEN WATER



Source "ERTS MSS Imagery"

LITTLE CHICAGO QUADRANGLE, MINN

CHANGES OF VISIBLE OPEN WATER



Source: "ERTS MSS Imagery"

SECTION II

TURBIDITY IN EXTREME WESTERN LAKE SUPERIOR

Dr. Michael Sydor
Department of Physics
University of Minnesota, Duluth

Index

N76 14571

TURBIDITY IN EXTREME WESTERN LAKE SUPERIOR

Investigator: Dr. Michael Sydor
Department of Physics
University of Minnesota, Duluth

The following data was prepared from ERTS images for western Lake Superior for 1972-74. The data was subdivided into categories representing various conditions of lake turbidity depending on the wind history.

Examination of the data, Fig. 1, 2, and 3, shows that for easterly winds the turbidity originating along the Wisconsin shore and the resuspension areas is transported northward then out along a N.E. path where it disperses, and often, for large storms, contaminates the Duluth water intake. Contaminants such as dredging fines anywhere along these paths would likewise find their way to the intake areas in concentrations comparable to the relative red clay concentration. The turbidity distribution in Fig. 1 was obtained from correlation of in situ measurements with the ERTS data. The transport paths were obtained from considerations of plume shapes and turbidity concentration gradients observed on ERTS images. The resuspension areas were obtained from comparison of turbidities on the lake for various wind conditions and examination of the relative turbidity concentration for easterly storms in comparison to the turbidity for known source areas, Fig. 4.

Examination of turbidity for westerly winds following an easterly storm, Fig. 5, indicates how the turbidity on the lake is flushed out by westerly winds due to the influx of clearer water from the north shore area. This can be seen by superposition of transparencies for Figs. 5 and 1 (See Figure 5a).

Westerly winds have a cleaning effect on the lake turbidity in the central area, but produce severe turbidity along the south shore. Fig. 6 shows the turbidity concentrations along the Wisconsin shore. This correlates very well with the relative erosion data, Fig. 4, based on survey data compiled by Hess.[1] This correlation can be seen by superposition of transparencies for Figs. 6 and 4 (See Figure 6a).

The shore erosion constitutes a relatively uniform source of turbidity. It is thus interesting to consider the dispersion of the turbidity perpendicular to the shore for variable wind conditions, Fig. 7.[2] Such data gives a measure of the dispersion length for fines of a turbidity source comparable to a red clay source, say dredgings from the Superior Entry area. Fig. 8 shows a plot of turbidity with distance from the shore.

Dredging fines would normally constitute a point source rather than a line source, thus Fig. 8 would represent an upper

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1. Charles Hess, Study of Shoreline Erosion on the Western Arm of Lake Superior.
2. Variable winds would result in random dispersion of the fines as against the drift or plume resulting from a steady wind. The resulting dispersion would be the consequence of a concentration gradient away from the shore.

value for plume dispersion of dredging fines for variable wind considerations (expected dispersion length is $\sim$ 2 miles for 1/e drop off).

The overall transport paths for turbidity, Figs. 2, 9, 10, 11, were derived from common features of turbidity plumes observed in ERTS images. Inspection of individual plumes, and in situ measurements[3,4] reveal that a current pattern for any particular event is rather complex with eddy structure depending on the wind history and the lake shore features. The eddy structure is important since it is responsible for prolonged periods of turbidity in the extreme western end of the Lake. Aside from effects due to severe storms, the turbidity in the Duluth-Superior area is generally considerably higher than the average turbidity in western Lake Superior, (3 mg/l suspended solids near Duluth vs. .5 mg/l, 5 miles off Knife River). This results from occurrence of current patterns which tend to keep the remnants of turbidity due to storms and the water from the St. Louis River and Duluth Harbor confined to the extreme western arm of the Lake. This is indicated by the average turbidity distribution in extreme western Lake Superior shown in Fig. 12. The effect of harbor effluents on the ten mile square of the tip of western Lake Superior is thus quite pronounced, and should be emphasized whenever pollution of the harbor is considered since

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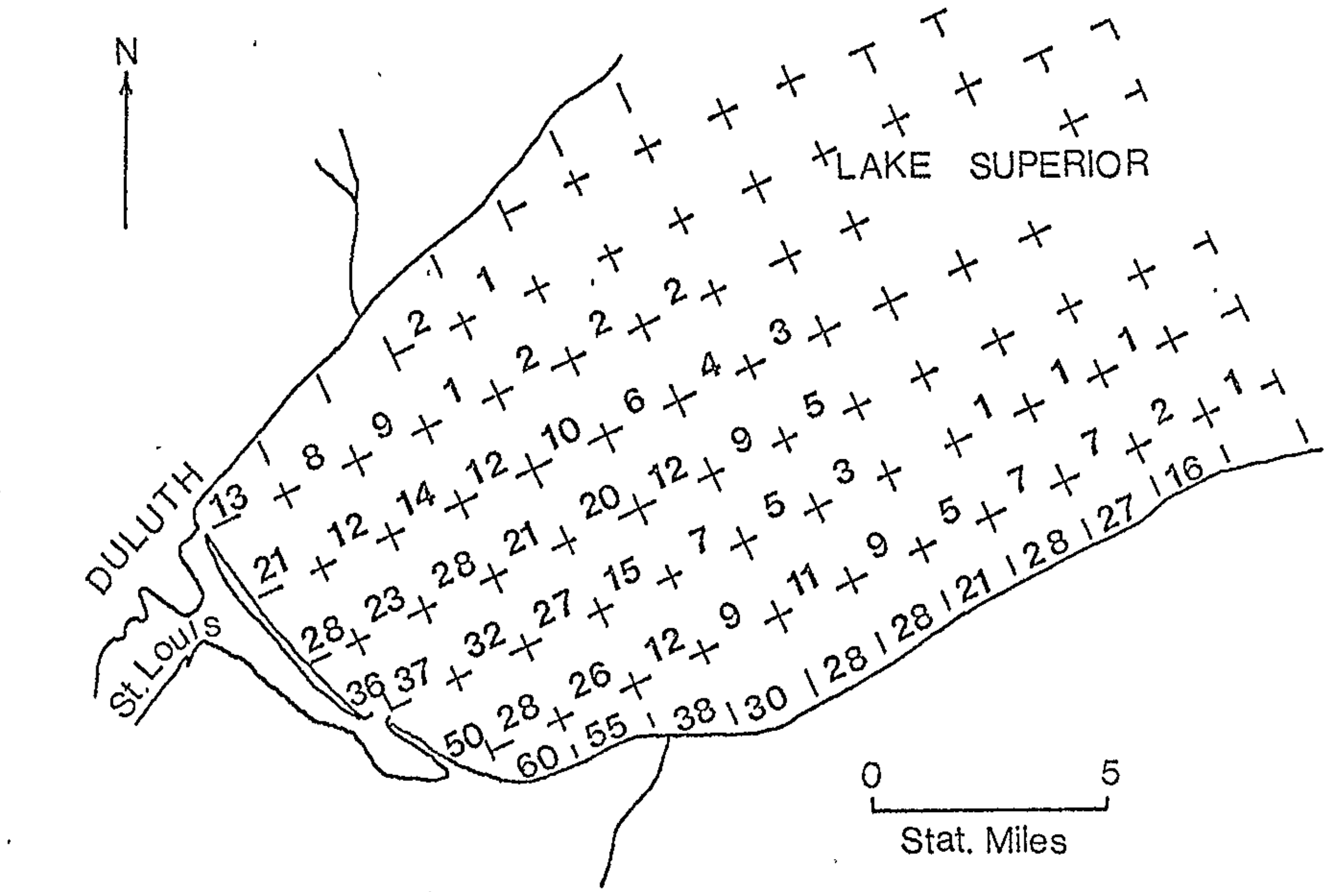
3. M. Sydor, Current Patterns and Turbidity in Extreme Western Lake Superior. DACW 37-74-6-0014.
4. M. Sydor, Preliminary Evaluation of Red Clay Turbidity Sources for Western Lake Superior. EPA R005175-1.

the affected area contains public water intakes, Fig. 13. Concentration of pollutants from the harbor area or dredging sites transported thru fines are expected to reach the Duluth water intake at roughly 0.2% concentration on the average and roughly 2% at the Cloquet intake. The effect of the harbor effluents on people and aquatic life is not known. However, the concern for the effects and extent of pollution in the Duluth-Superior Harbor should be commensurate with the concerns for pollution of Lake Superior itself.

With the possibility of resumption of the disposal of dredgings in Lake Superior, we would like to encourage the pursuit by the Corps of studies of effects of dredging on the Lake Superior environment (inside and outside of the bay areas). We would also suggest that the present deep water disposal sites are unsuitable in terms of their proximity to water intakes and that alternative sites, at least for experimental purposes, be sought in the area a few miles east of the Superior Entry. The near beach disposal should be accompanied by studies of the effects of dredgings on lake biota, and measurements for the determination of the extent of the affected areas. Furthermore, a comprehensive, long range study of the harbor area including the shallower areas away from the shipping channel, would be a significant step towards the understanding of the effects of dredging operation, ship traffic, and the effects of pollution abatement on the harbor. Much of the efforts in past studies for these areas were short range, in response to urgent needs for investigation because of impending actions for maintenance or construction. Most of the past data is sparse, insufficient to separate the temporal and spatial variations as was exemplified by the recent changes in pollution classification of the harbor. With the possibility of eventual harbor deepening necessitated by economic considerations, and the continual need for dredging and disposal in regular maintenance, a long range study of the harbor would be very fruitful in understanding the environmental problems for decision making purposes pertaining to maintenance and construction and for the purpose of reclamation of the lower St. Louis River area from its current pitiful condition.



Relative turbidity for Easterly storm

Fig. 1

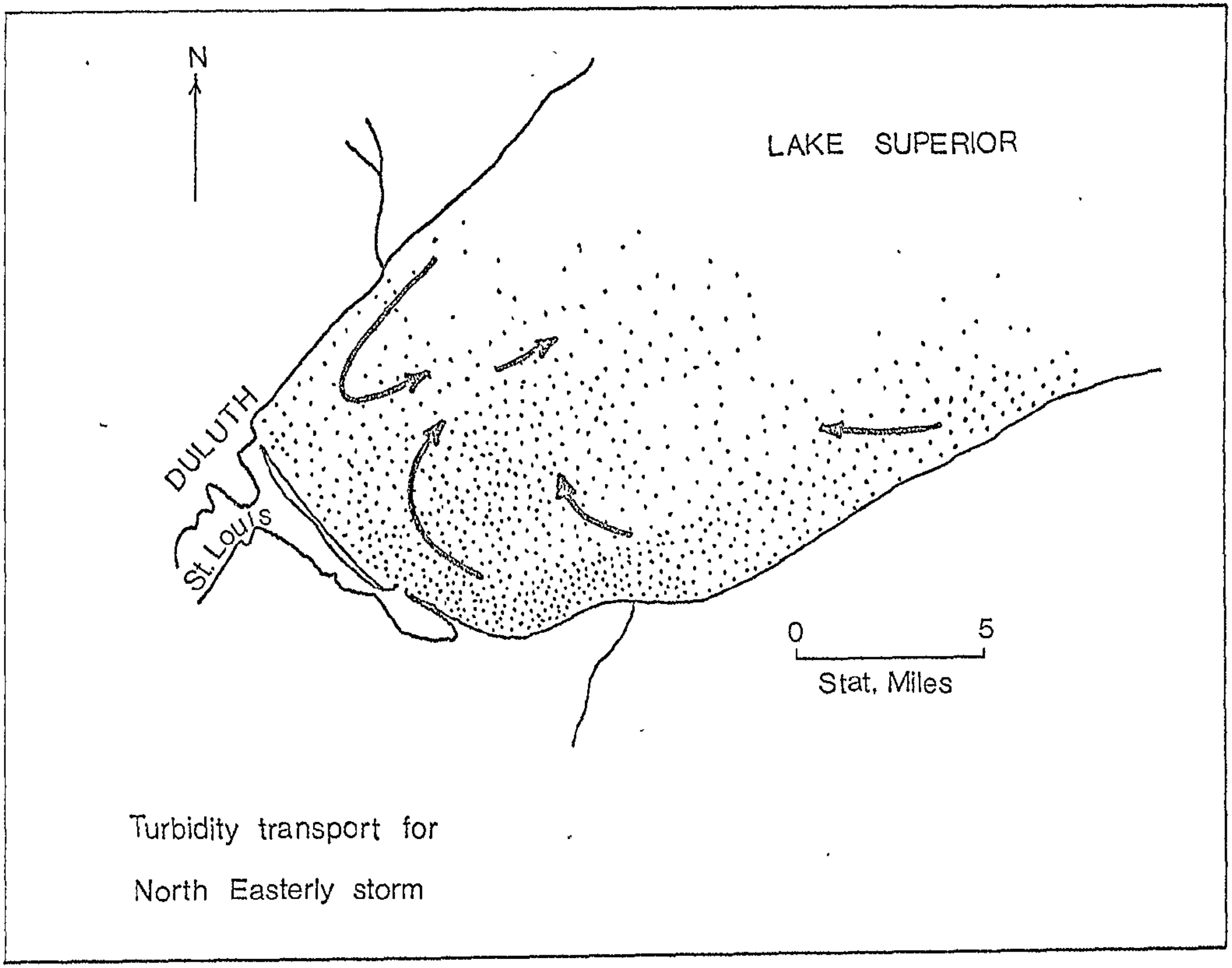

N
LAKE SUPERIOR
DULUTH
St. Louis
0
5
Stat, Miles
Turbidity transport for
North Easterly storm

Fig. 2

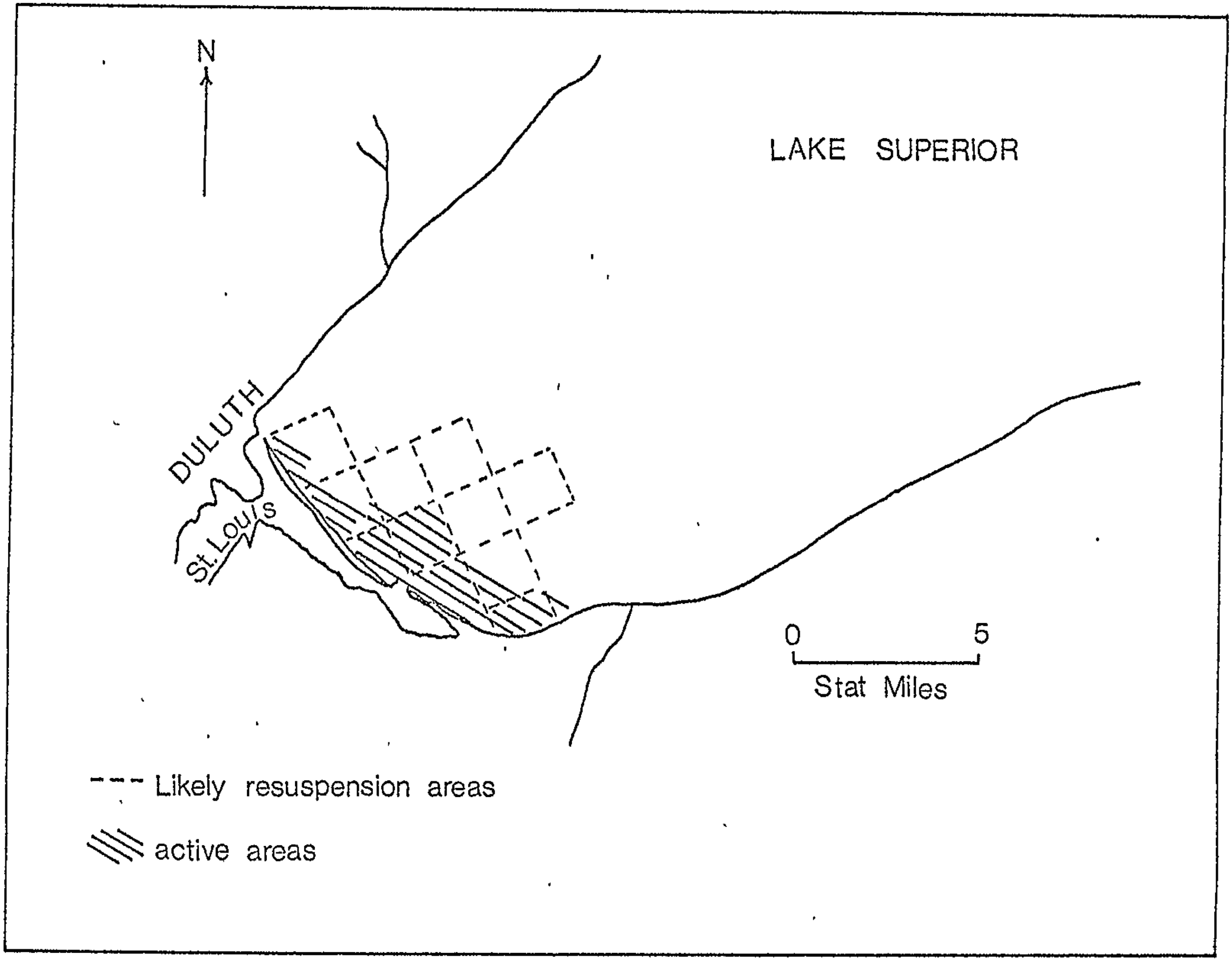
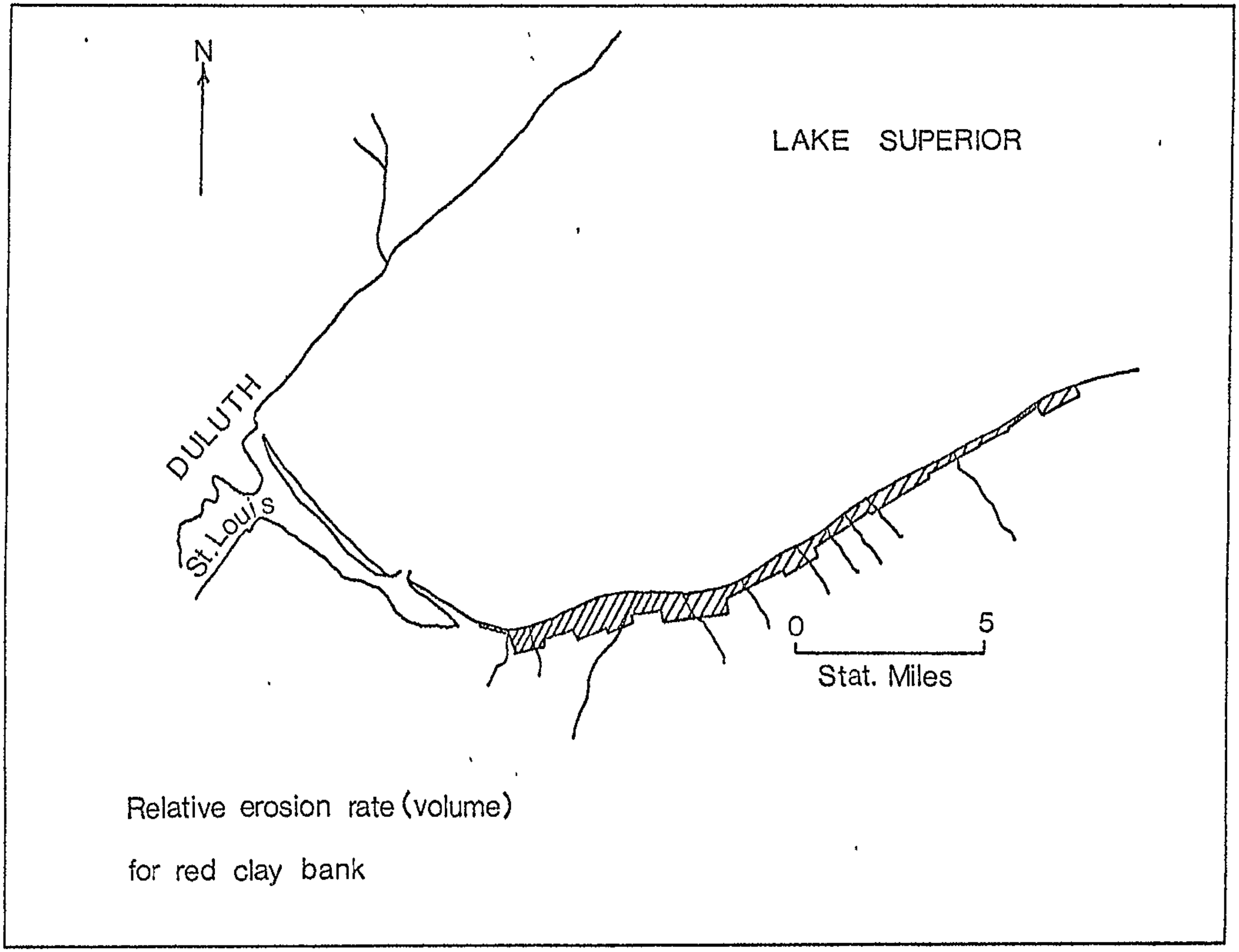
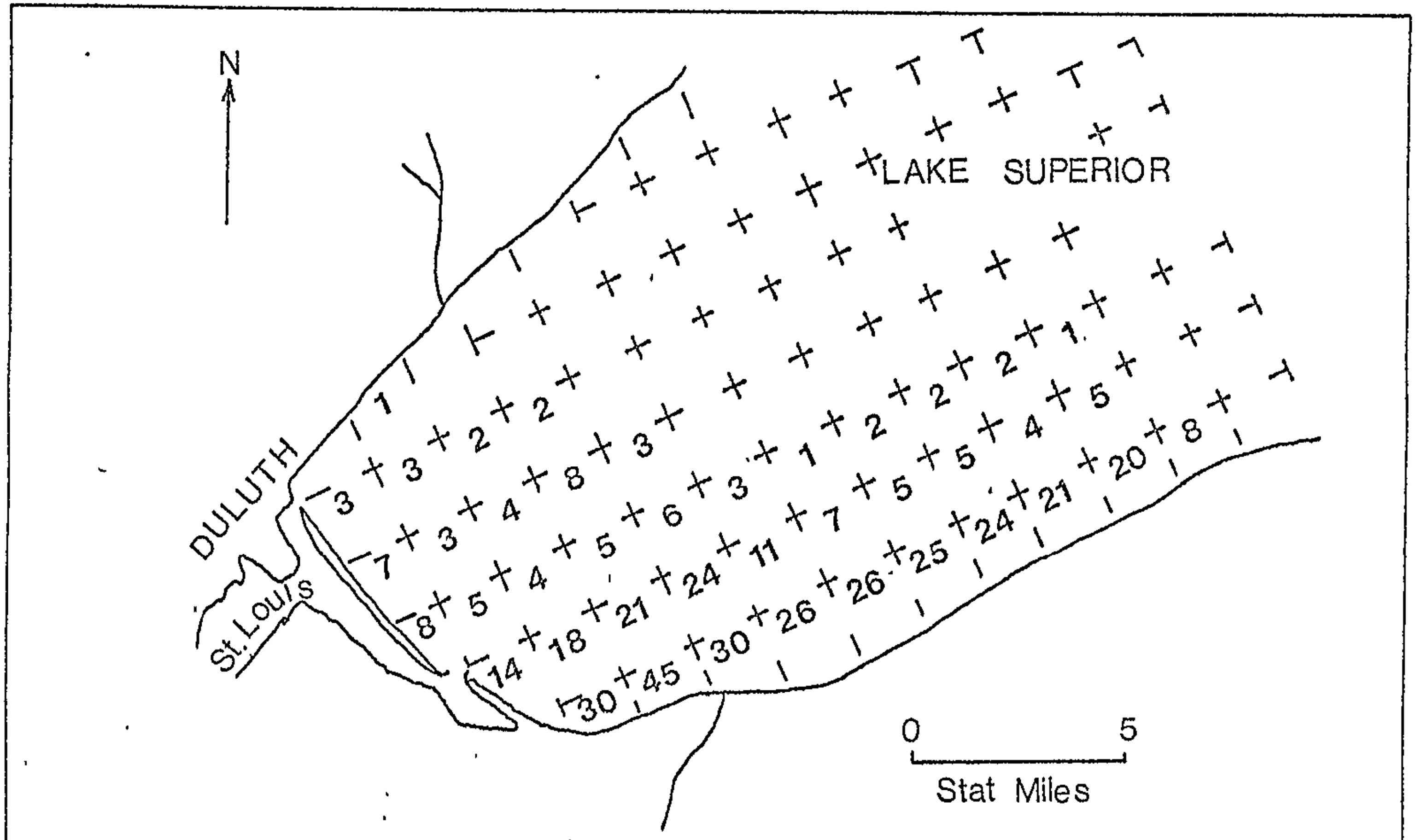

N
LAKE SUPERIOR
DULUTH
St. Louis
0
5
Stat Miles
Likely resuspension areas
active areas

Fig. 3



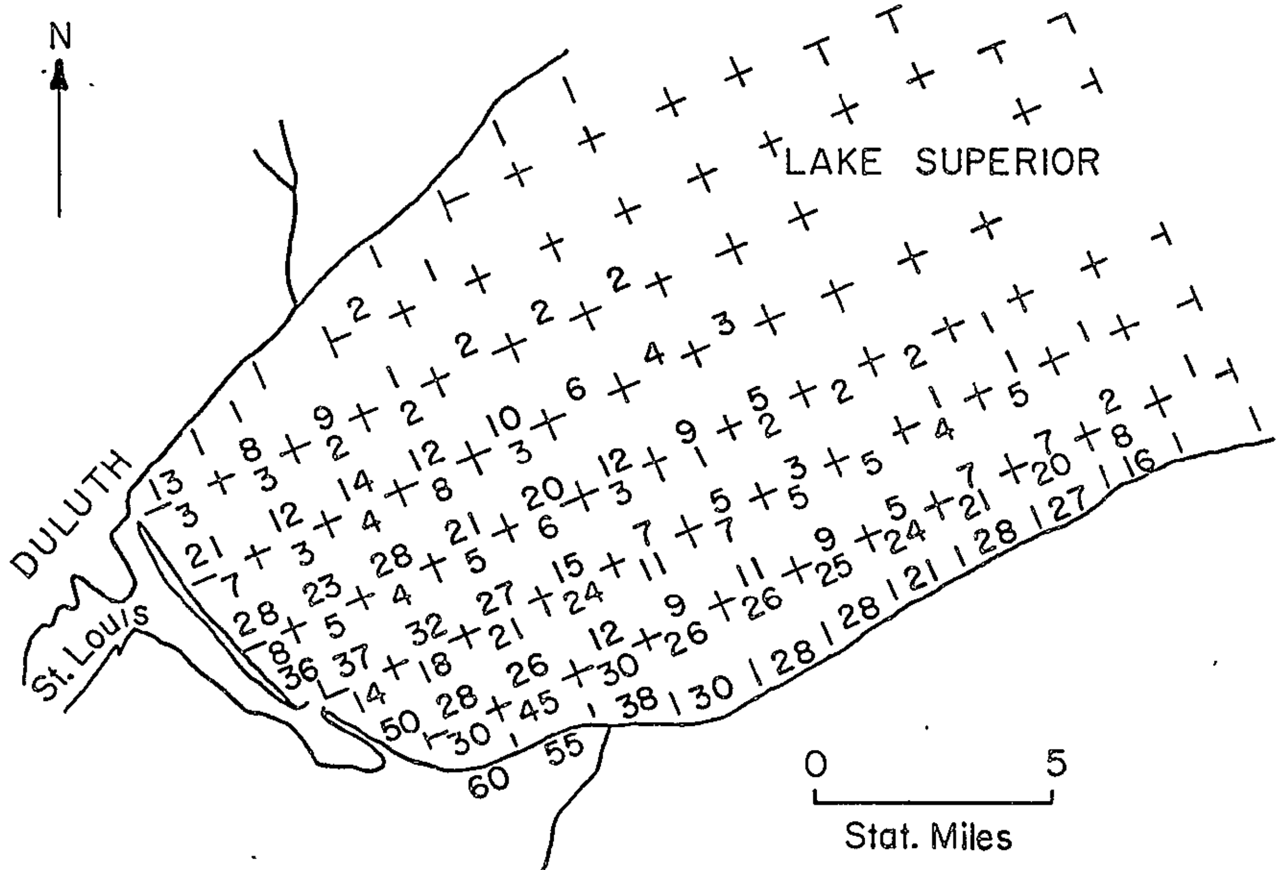
Relative erosion rate (volume) for red clay bank

Fig.4



Relative turbidity for Easterly storm followed by westerly dispersion

Fig. 5

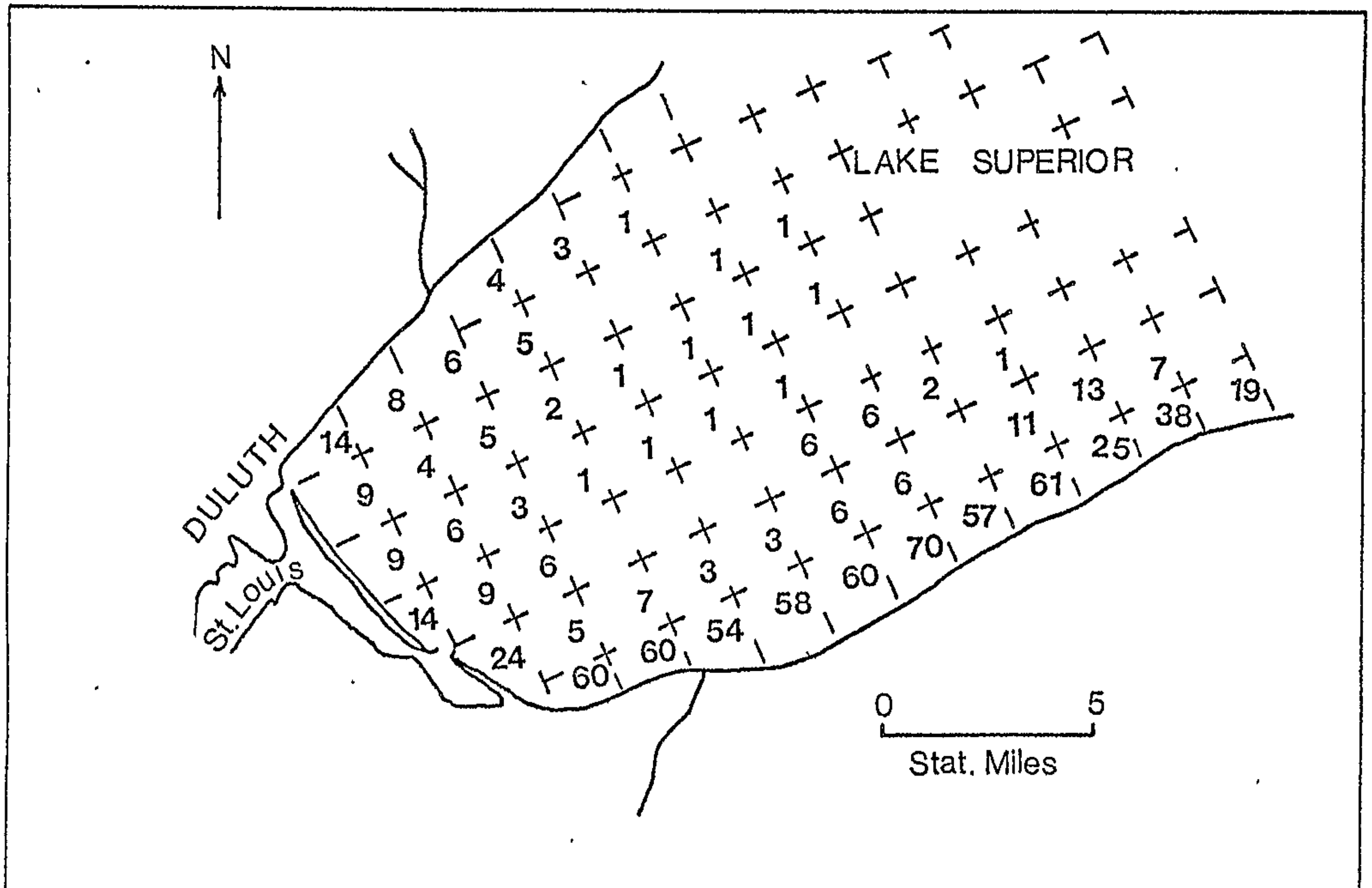


Superposition of:

Relative turbidity for Easterly storm (Fig. 1)

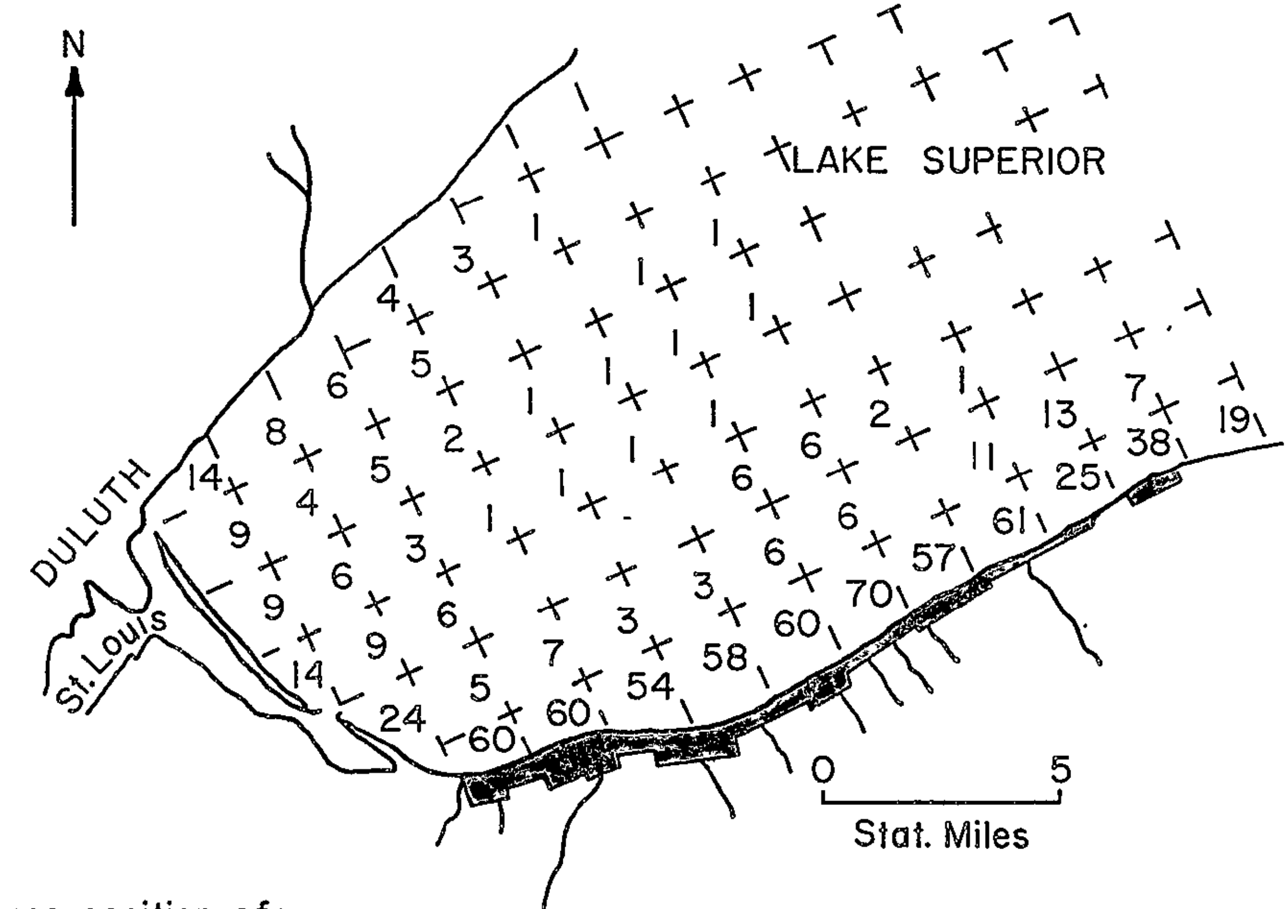
Relative turbidity for Easterly storm
followed by westerly dispersion (Fig. 5)

Fig. 5a



Relative turbidity for N.W. & W. winds

Fig. 6

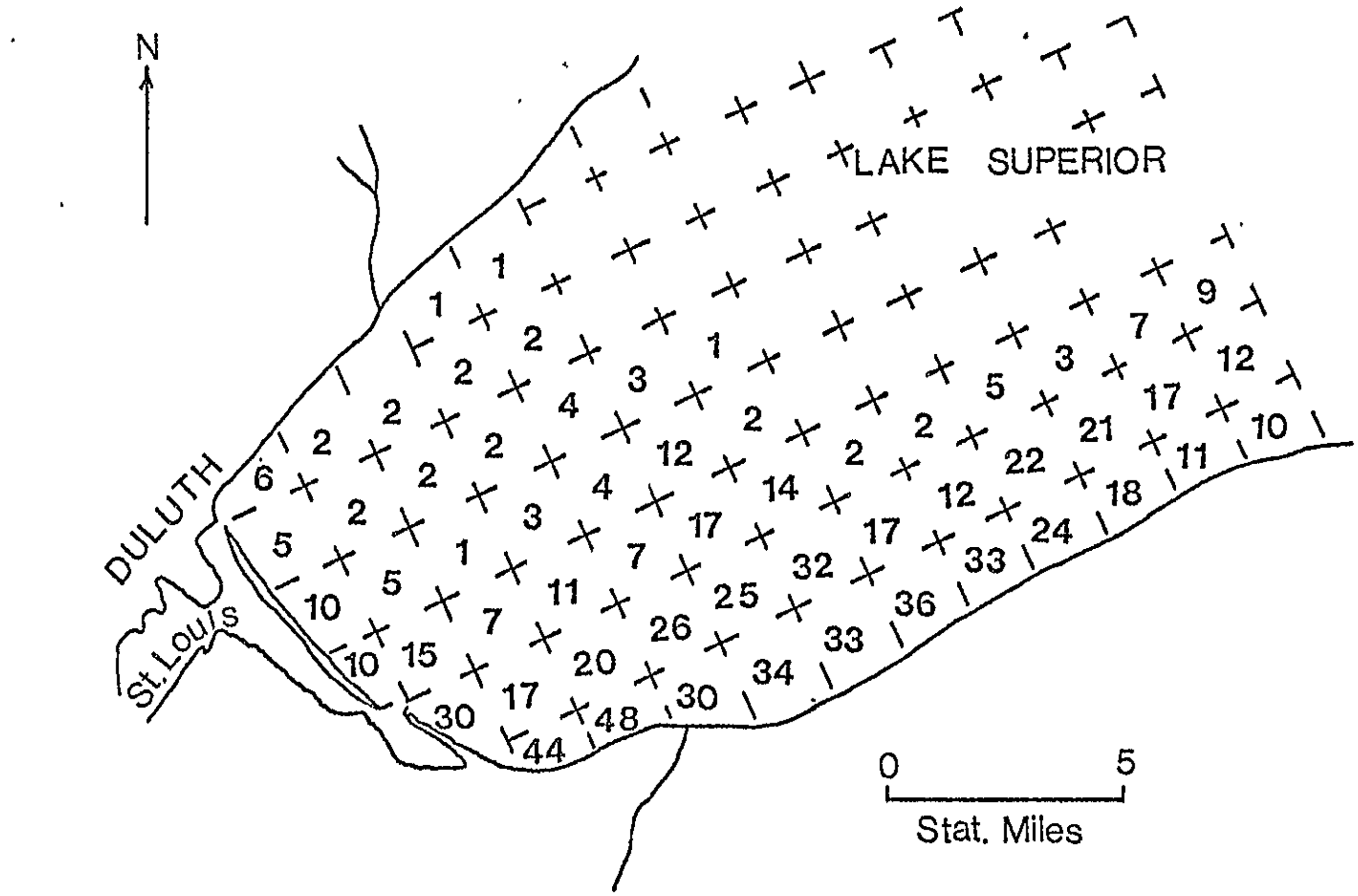


Superposition of:

Relative turbidity for N.W. & W. winds (Fig. 6)

Relative erosion rate (volume) for red clay bank (Fig. 4)

Fig. 6a



Relative turbidity for variable winds

Fig.7

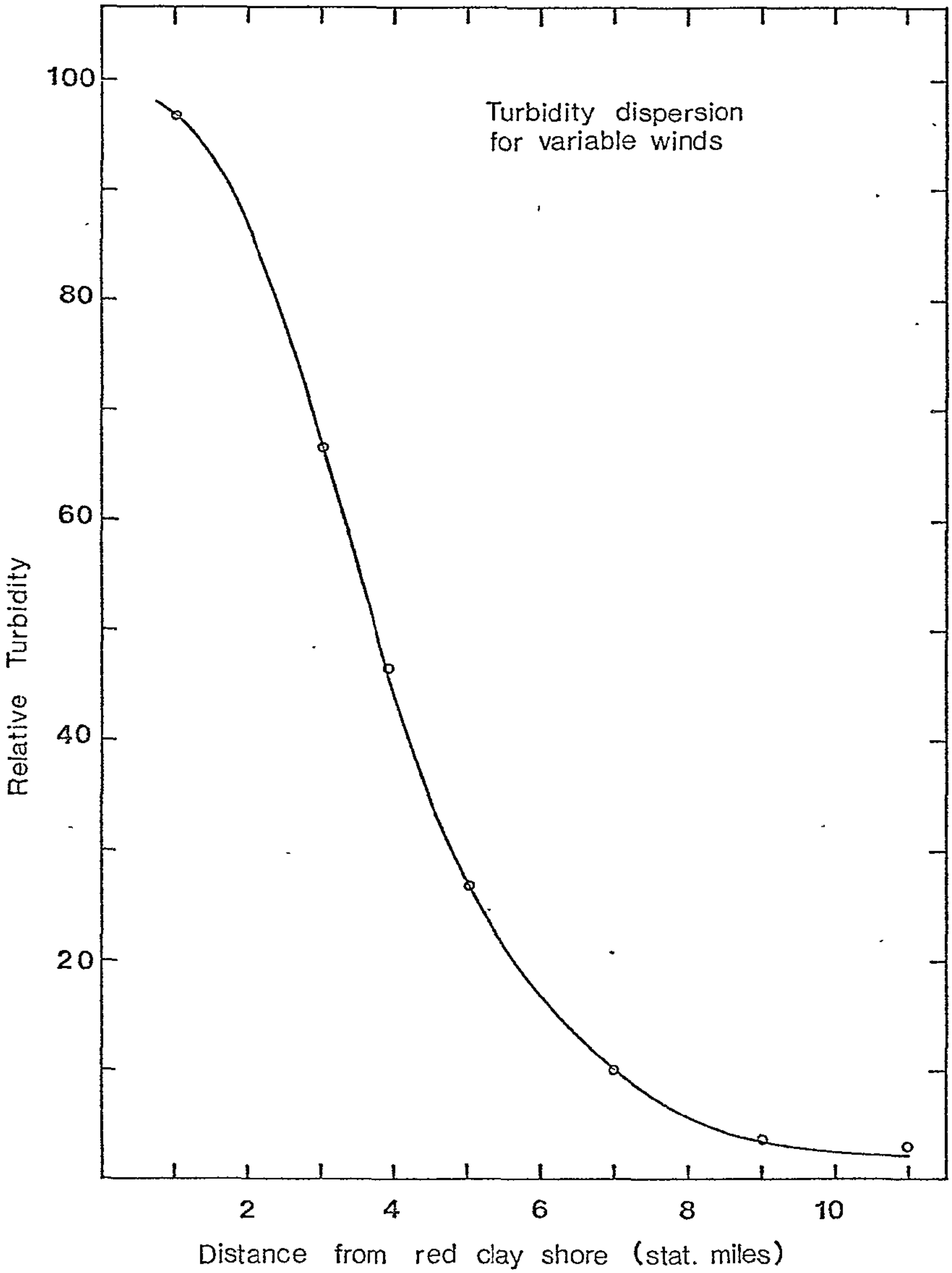
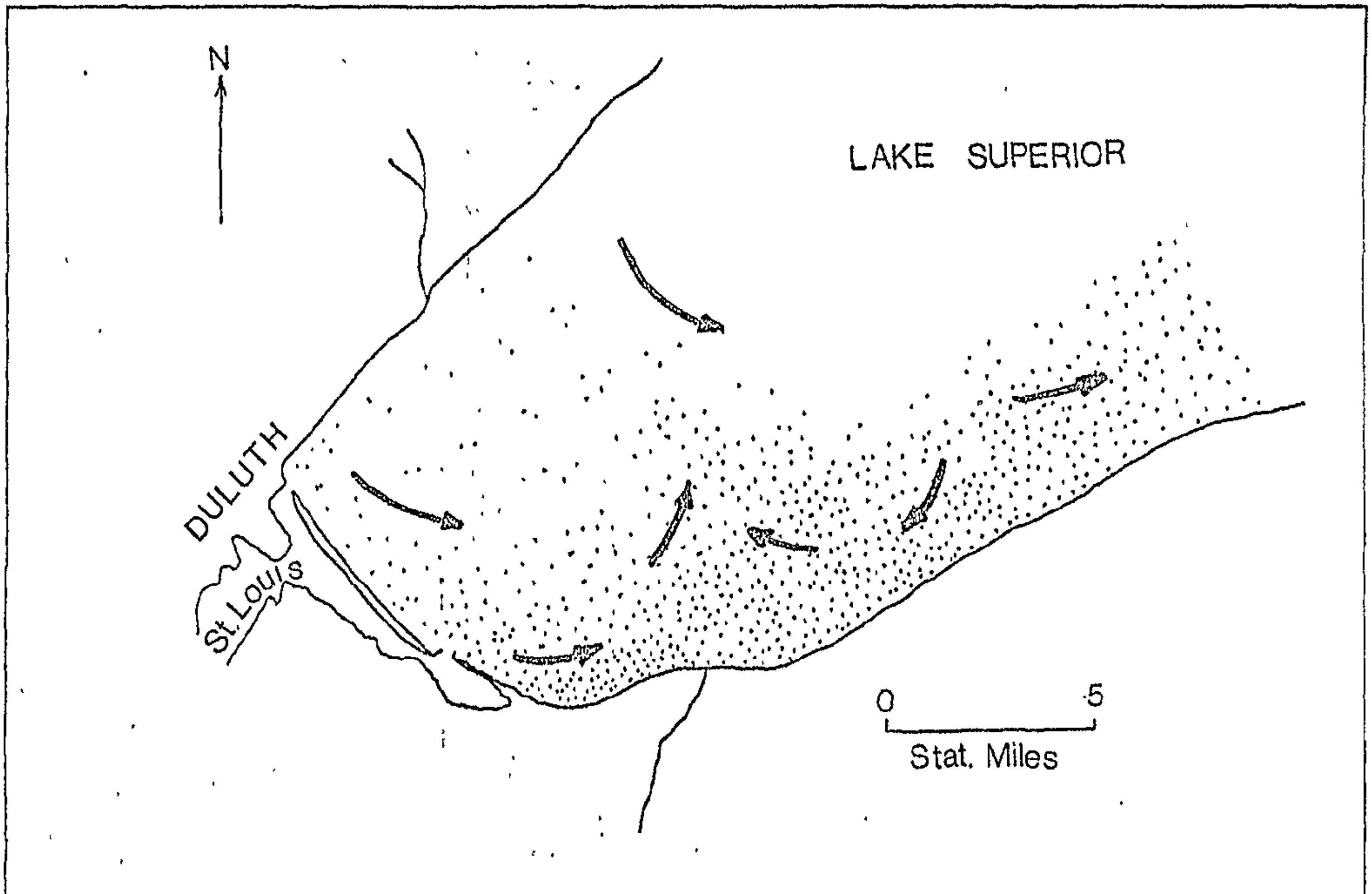

Turbidity dispersion for variable winds
100
80
60
40
20
Relative Turbidity
2
4
6
8
10
Distance from red clay shore (stat. miles)

Fig.8



Turbidity dispersion for variable winds

Fig. 9

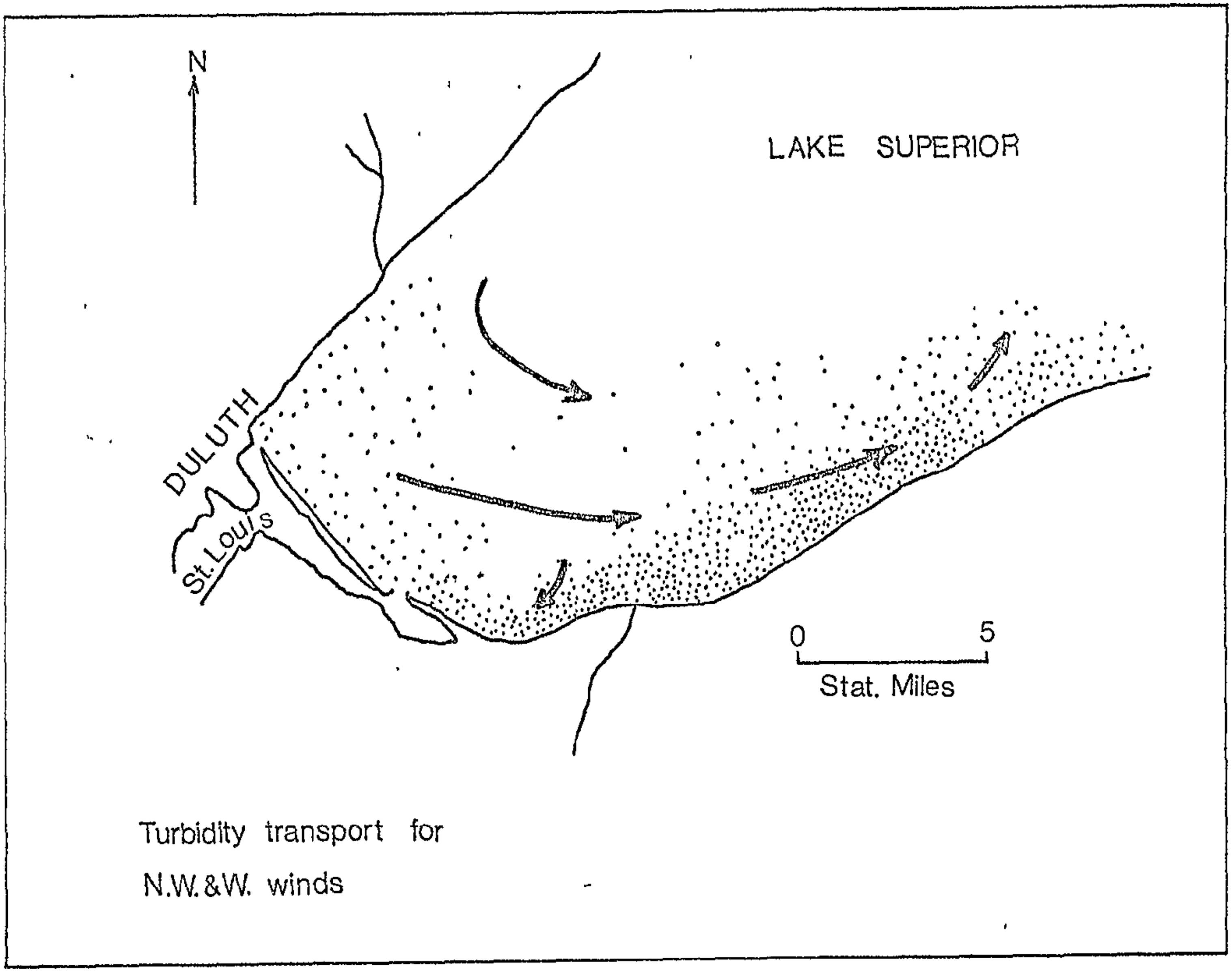

N
LAKE SUPERIOR
DULUTH
St. Louis
0
5
Stat. Miles
Turbidity transport for
N.W.&W. winds

Fig. 10

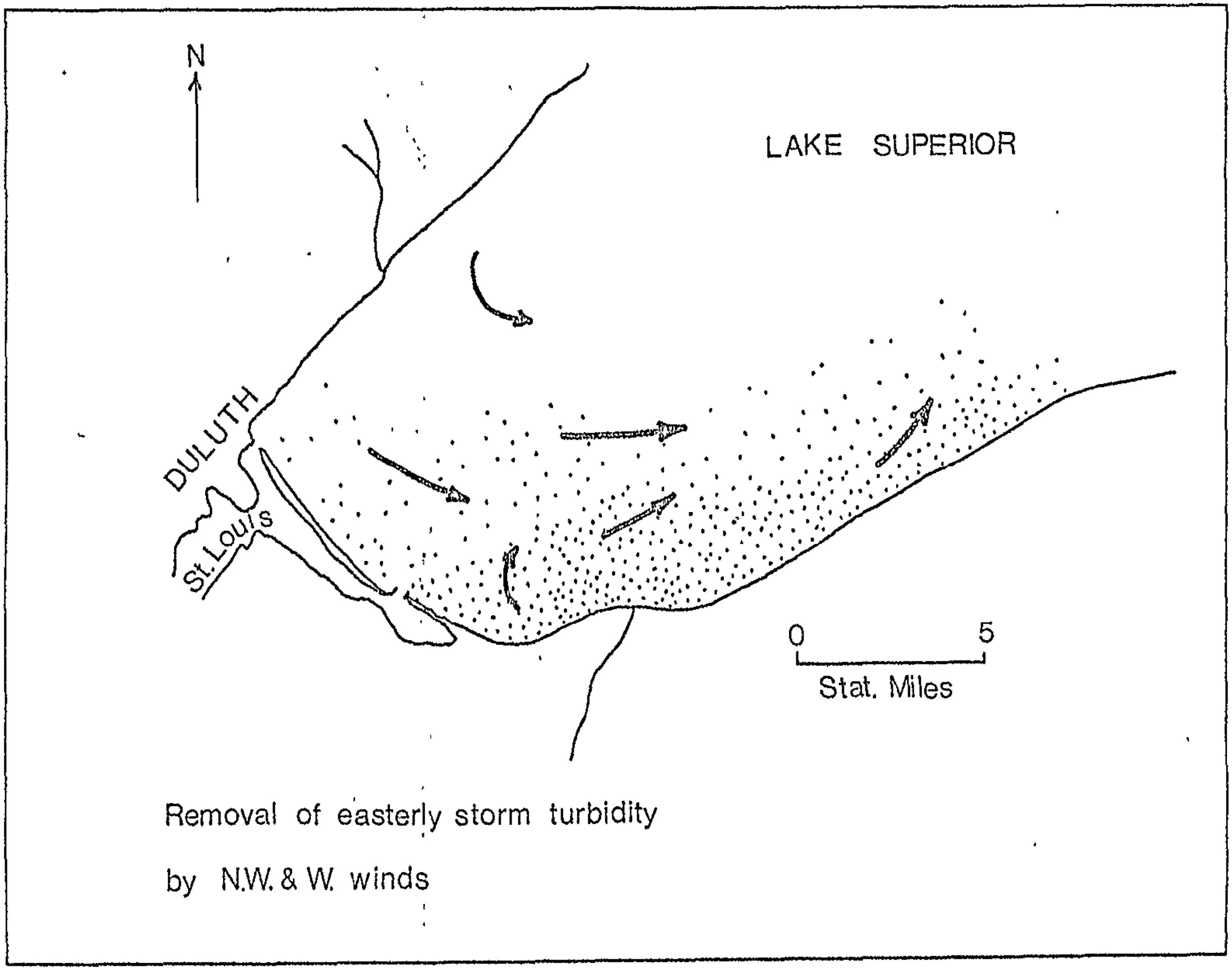

N
LAKE SUPERIOR
DULUTH
St. Louis
0
5
Stat. Miles
Removal of easterly storm turbidity
by N.W. & W. winds

Fig. 11

C.2

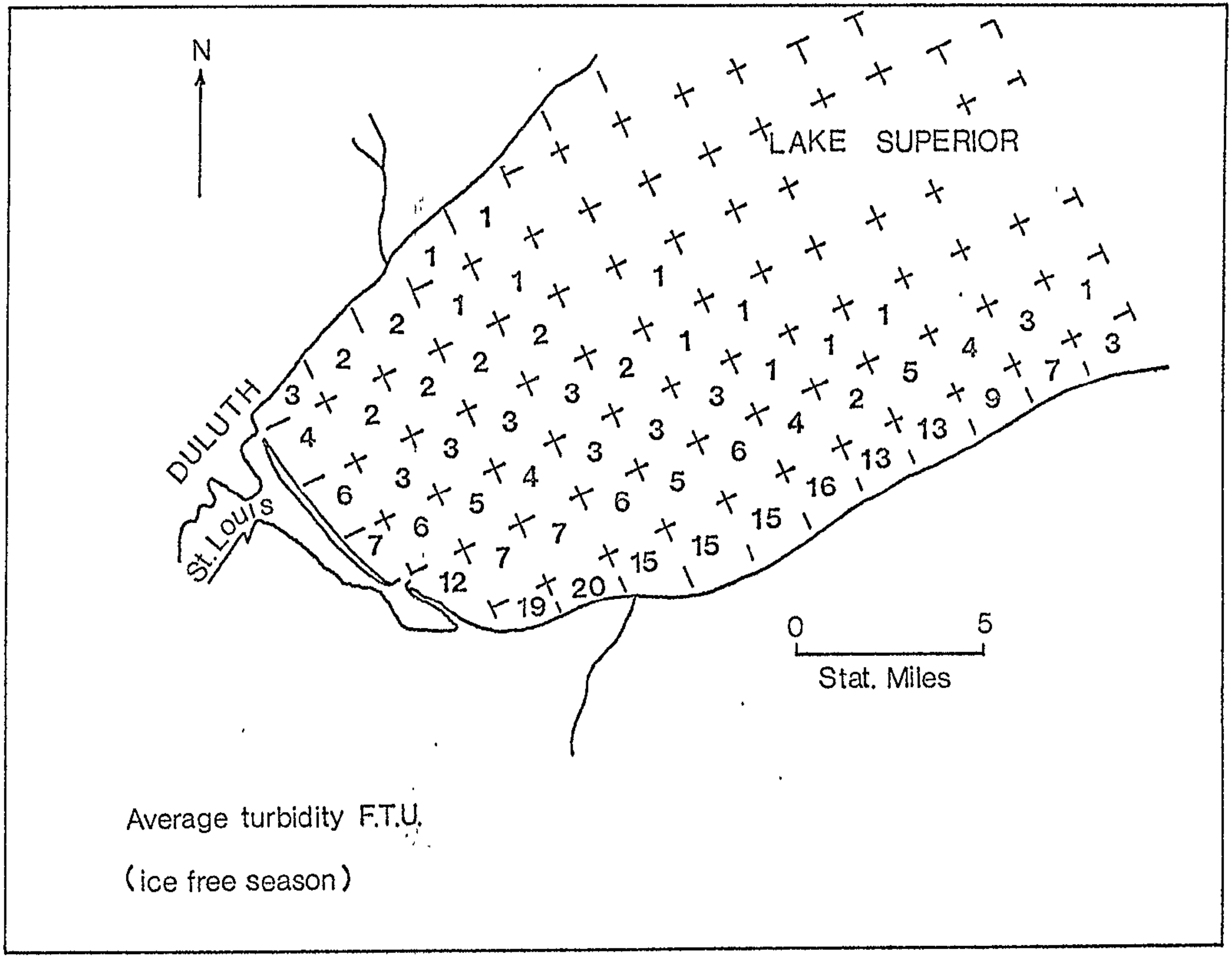

N
LAKE SUPERIOR
DULUTH
St. Louis
0
5
Stat. Miles
Average turbidity F.T.U.
(ice free season)

Fig. 12

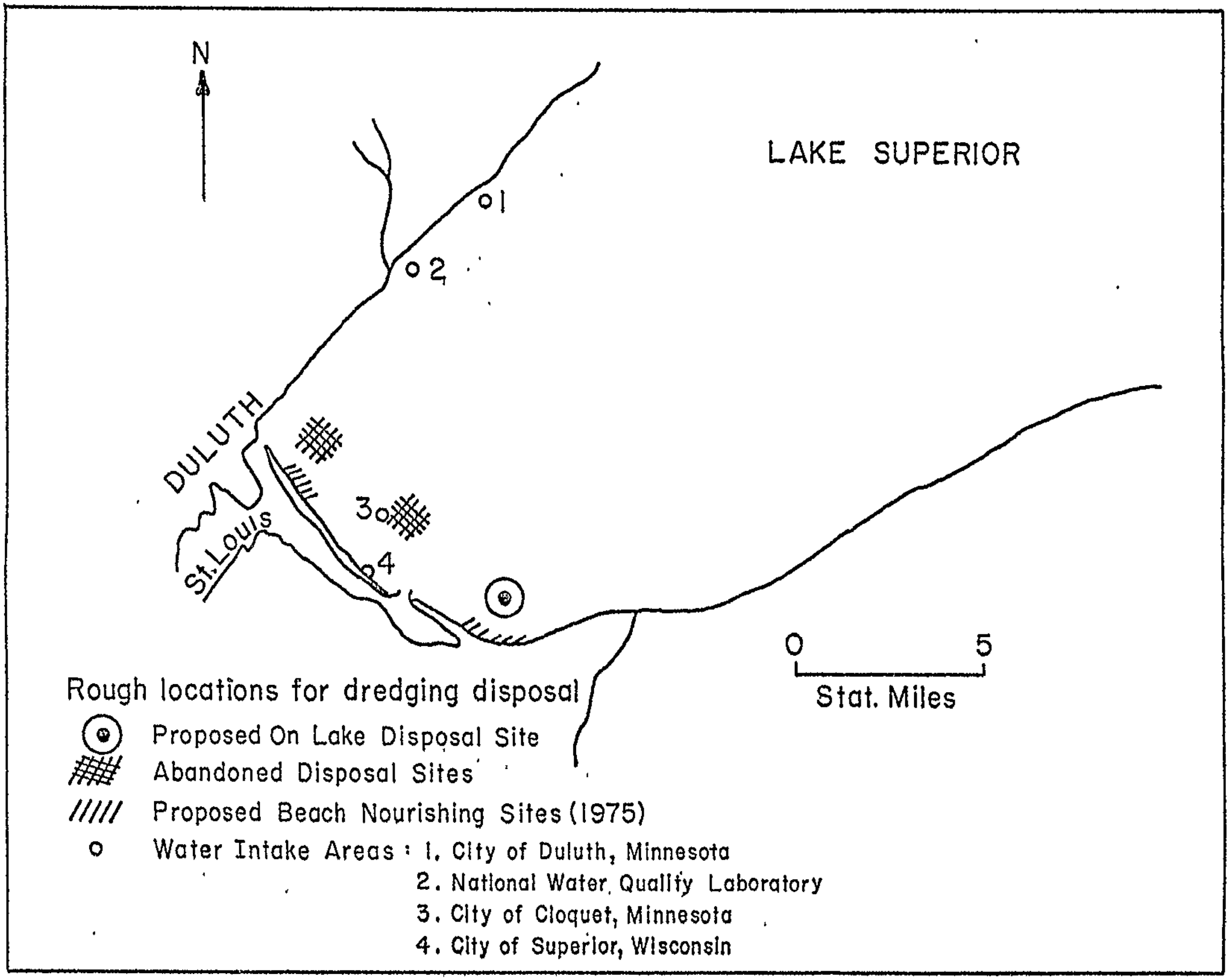

N
LAKE SUPERIOR
DULUTH
St. Louis
o1
o2
3o
o4
0
5
Stat. Miles
Rough locations for dredging disposal
Proposed On Lake Disposal Site
Abandoned Disposal Sites
Proposed Beach Nourishing Sites (1975)
Water Intake Areas : 1. City of Duluth, Minnesota
2. National Water Quality Laboratory
3. City of Cloquet, Minnesota
4. City of Superior, Wisconsin

Fig. 13

DEPARTMENT OF THE ARMY
ST. PAUL DISTRICT. CORPS OF ENGINEERS
1135 U. S. POST OFFICE & CUSTOM HOUSE
ST. PAUL. MINNESOTA 55101

IN REPLY REFER TO
NCSED-ER

6 August 1975

Dr. Michael Sydor
Professor of Physics
University of Minnesota-Duluth
Duluth, Minnesota 55812

Dear Dr. Sydor:

Discussions have taken place during the past month between yourself and representatives of the St. Paul District regarding the potential for designating a new open-lake disposal site for dredged material from Duluth-Superior harbor. The potential use of such a site would, of course, be applicable only to dredged material which has been classified as suitable for in-lake disposal. Based upon these discussions, we are considering the designation of an area 1 mile in diameter centered at coordinates 46° 42' 55" N, 91° 57' 50" W as this new disposal site. At the same time, the presently designated open-water disposal sites for the harbor (areas 1 mile in diameter centered at 46° 46' 30" N, 92° 03' 25" W and 46° 44' 25" N, 92° 00' 00" W) would be abandoned.

We would appreciate your comments on this concept in general and, based upon your knowledge of the water transport system operating in the western arm of Lake Superior, an assessment of the effects disposal at this new site could have on the area's water supply intakes. Please include a comparison of these effects with those which could be expected from the use of the presently designed disposal sites.

Sincerely yours,

Wm. L. Goetz

W. L. GOETZ
Chief, Construction Operations
Division

UNIVERSITY OF MINNESOTA
DULUTH

Department of Physics
271 Classroom Laboratory Building
Duluth, Minnesota 55812

August 19, 1975

W. L. Goetz
Chief, Construction Operations Division
Department of the Army
St. Paul District, Corps of Engineers
1135 U. S. Post Office & Custom House
St. Paul, MN 55101

Dear Sir:

In reply to your letter of August 6, 1975, please find enclosed a report on transport processes in Western Lake Superior which was determined from ERTS data (NASA contract NGL 24 005 263) and in situ measurements. We have made numerous measurements on currents and turbidities in the proposed disposal site. Also enclosed is a map (A) prepared from numerical model on the Lake transports. It corroborates the results obtained from the remote sensing data. The former dredging disposal sites in the Duluth area would directly affect water quality at all municipal water intakes for easterly wind conditions. The proposed site lies in a more favorable location in comparison to the former sites, because the transport patterns would, for all measured cases, disperse the leechate in the Lake along paths which lie farther away from the Duluth intake.

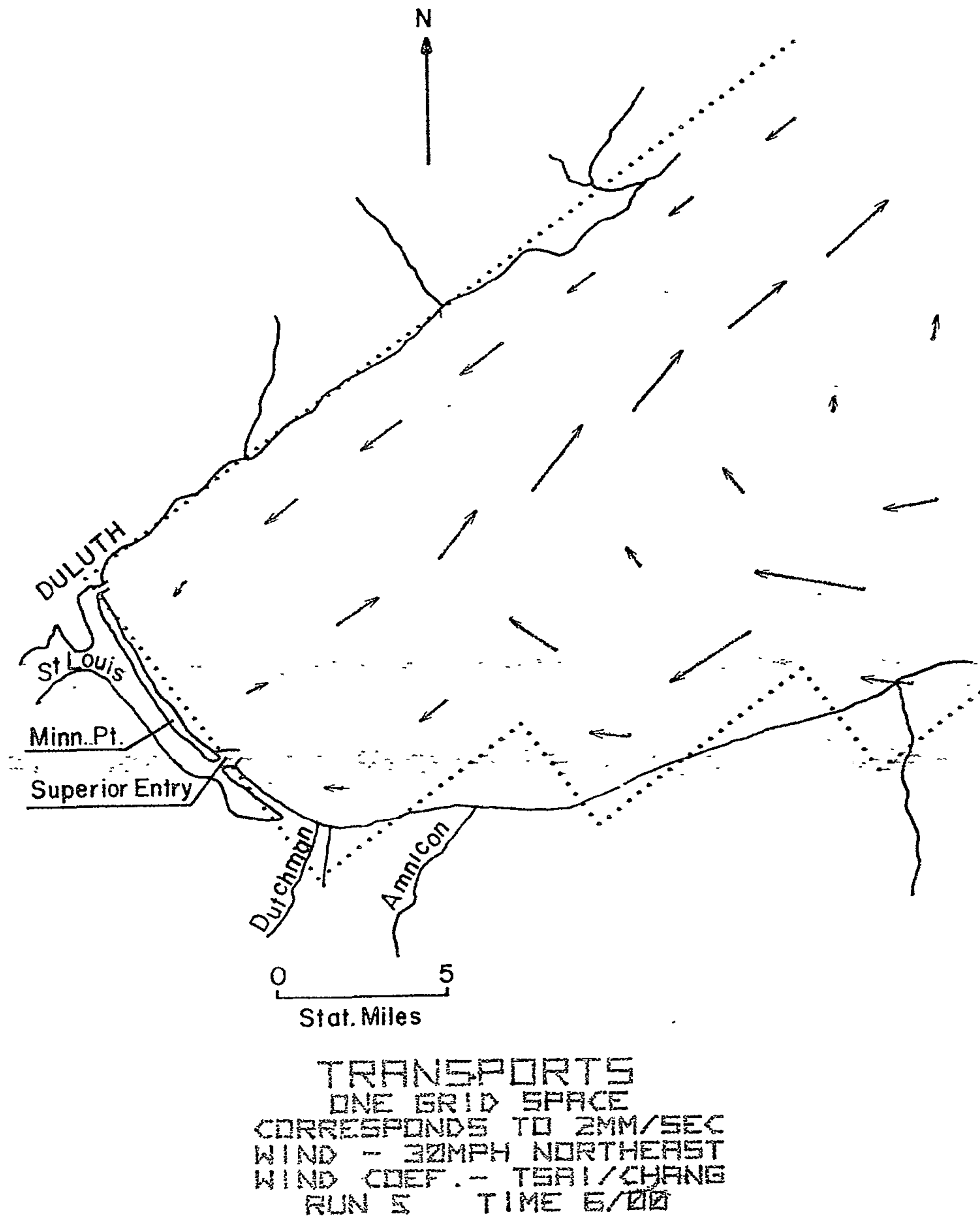
Sincerely,

M. Sydor

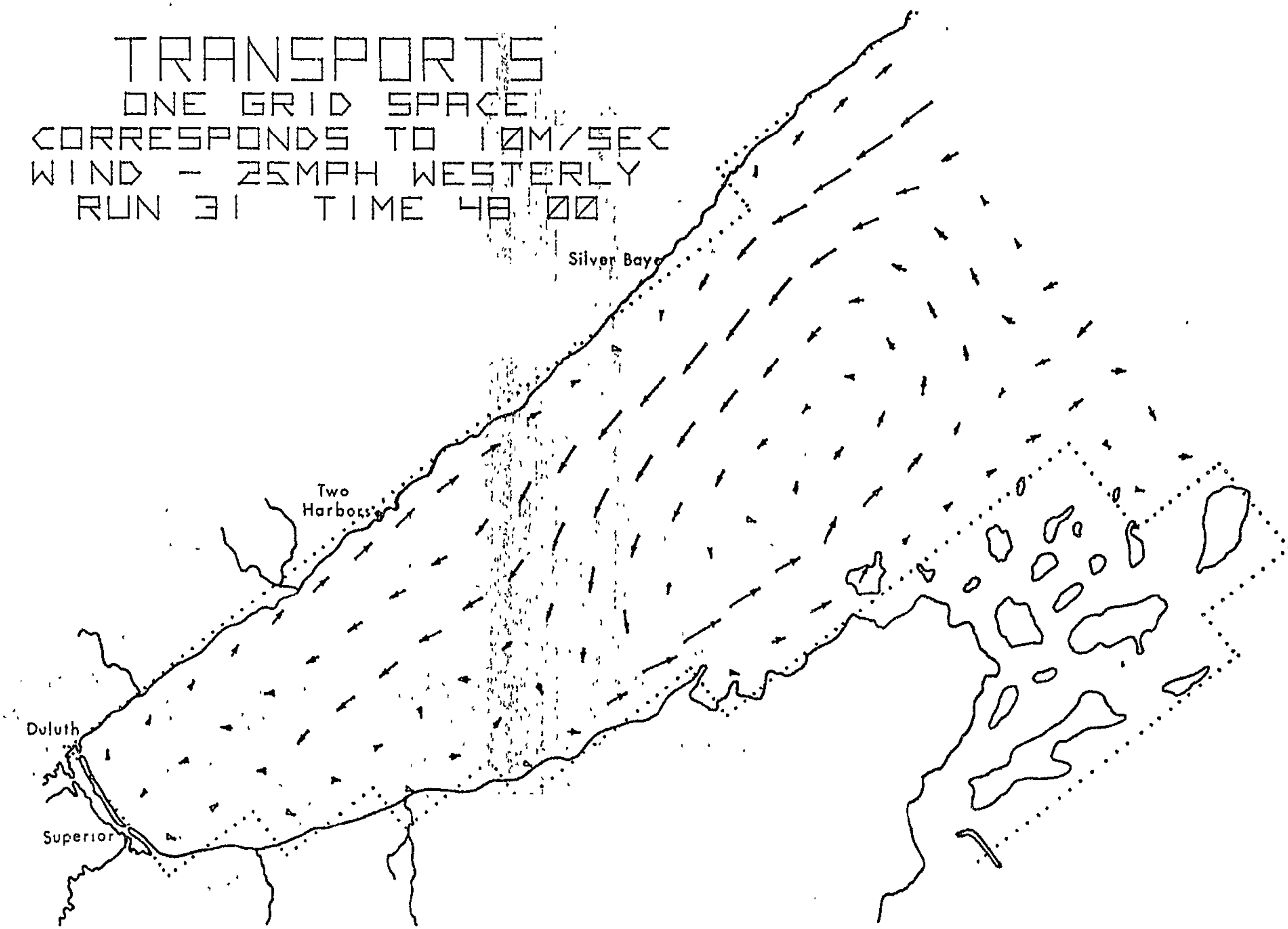
Michael Sydor
Professor

MS:dh

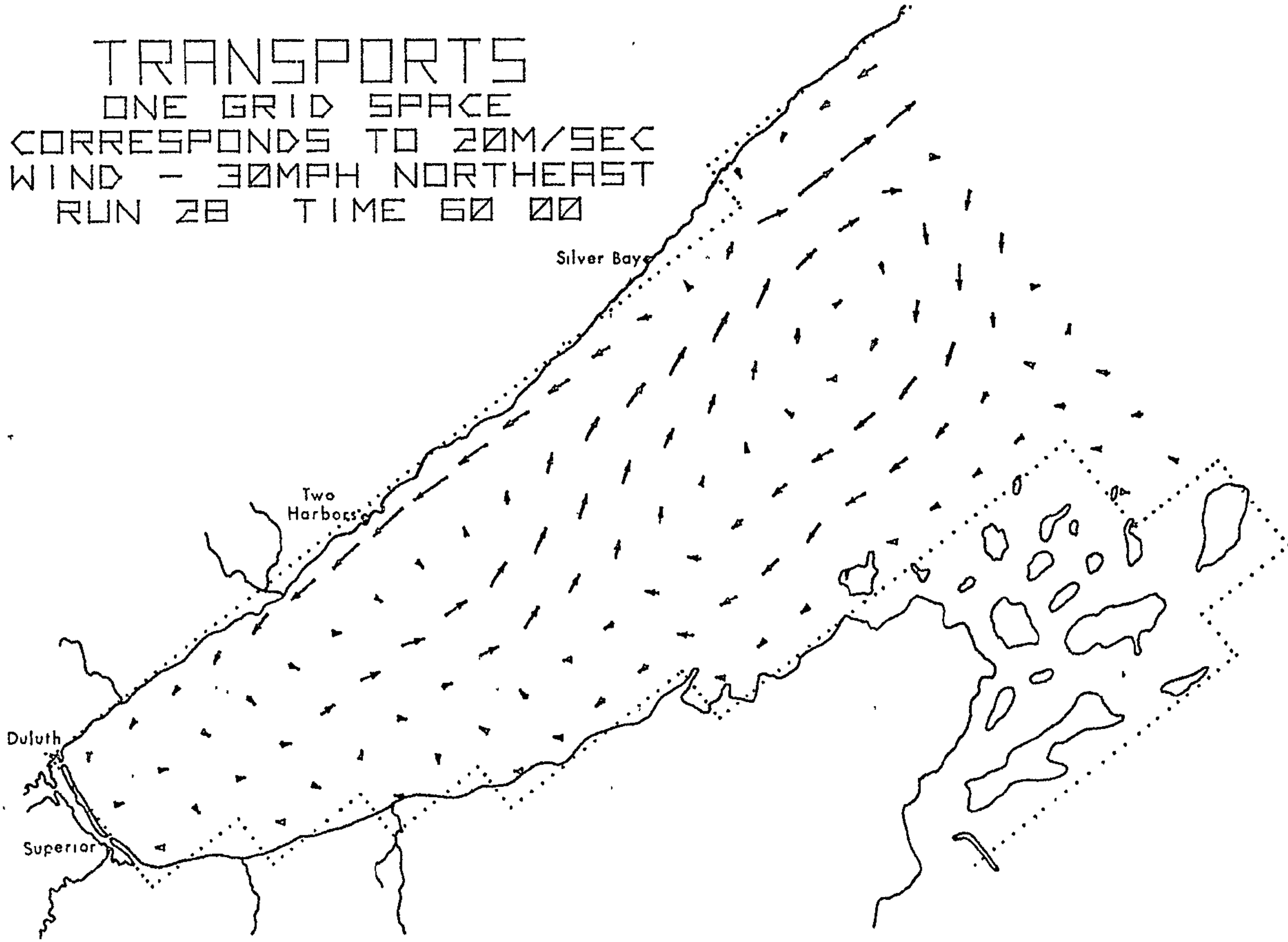
cc: J. Vitale
W. Shepherd ✓
R. Berry



MAP A LAKE TRANSPORT



MAP B LAKE TRANSPORT



MAP C LAKE TRANSPORT

SECTION III

REMOTE SENSING APPLICATIONS TO GEOLOGY IN MINNESOTA

Dr. Matt S. Walton
Minnesota Geological Survey
St. Paul, Minnesota

Index

N76 14572

APPLICATIONS OF ERTS IMAGERY TO MAPPINGS SEDIMENTS OF THE TWIN CITIES METROPOLITAN AREA

Investigator: Mr. J. R. Poppe
Minnesota Geological Survey
St. Paul, Minnesota

The Minnesota Geological Survey initiated a preliminary study of the applications of E.R.T.S. imagery to geological investigations in the Twin Cities Metropolitan area. The goal of the project was to compare E.R.T.S. imagery to surficial geologic maps, prepared through traditional field studies. Lithologic boundaries, bedrock outcrops, bedrock structures and geomorphologic features were examined and compared with E.R.T.S. color-tone changes.

E.R.T.S. false-color 9" x 9" transparencies were supplied by the Department of Geography, University of Minnesota. These transparencies were converted to 35mm slides and were projected to increase detail. The transparency with the best resolution was produced April 4, 1973, and was selected as the photographic base.

Two areas of investigation were identified for use in the Twin Cities Metropolitan area:

1. an area southeast of the Twin Cities, located chiefly in northern Dakota County, and
2. the New Brighton 15-minute quadrangle located in portions of Ramsey and Anoka Counties (see Fig. 1).

The study procedure included viewing the projected slides and recording all color changes. Bias was eliminated by initially studying E.R.T.S. without referring to the surficial geologic reference maps. The contacts between different lithologies taken from geologic maps of the Twin Cities Metropolitan area were compared with changes in color tones on E.R.T.S. photos. Finally, the geology of certain areas was field-checked where discrepancies existed between E.R.T.S. color boundaries and mapped lithologic contacts. Field work included detailed examination of natural and man-made exposures in roadcuts. The location, color, and type of glacial sediment was noted and samples were collected for later laboratory examination. The color changes in the metropolitan area, noted in the E.R.T.S. imagery, are related to different glacial lithologies, e.g., tills, outwash deposits, river and lake sands, and certain geomorphological features.

The visual comparison of geologic maps and E.R.T.S. imagery demonstrated the limitations of this approach to geological investigations. Bedrock outcrops and bedrock structure in the metropolitan area do not appear on E.R.T.S. imagery. However, certain glacial sediments can be identified and are potentially mappable. In one area, certain geomorphological features were discernable.

The Wisconsin Stage surficial deposits of Study Area One (Fig. 2) consist of Superior Lobe red till, Superior

Lobe red outwash deposits, and Des Moines Lobe buff-colored till. Four surficial geological reference maps, (Stone, 1965; Gelineau, 1959; Hogberg, 1970; Harms, et al., 1975) were compared with color-tone areas observed on E.R.T.S. imagery. The boundaries of the surficial deposits vary in specific localities, from map to map. However, the principal map used for the study was the regional surficial reconnaissance map prepared by John Stone (1965). For the most part, only minor variations between the boundaries of Stone's mapped lithologies and the E.R.T.S. color tones are apparent, when the map constructed from E.R.T.S. imagery is reduced to the 1:250,000 scale of Stone's map (Fig. 2). There are a few major differences between Stone's map and the map determined by E.R.T.S. imagery. These areas of discrepancy were field-checked and compared with Gelineau's (1959) detailed surficial maps. Gelineau's (1959) map compared favorably with Stone's (1965) map to the south of Grey Cloud Island (Fig. 2), Township 115, Range 18 and 19. Dr. H. E. Wright, Department of Geology, University of Minnesota (oral communication), interpreted the geomorphological features of this area as terraces. Field-checking verified the fact that Stone (1965) and Gelineau (1959) were correct in mapping the surficial lithology as Superior Lobe outwash. In this area, the map-line determined from E.R.T.S. imagery color changes only depicts the geomorphologic boundary between an upper and a lower terrace; it does not coincide with the correct boundary between till and outwash.

The second discrepancy between Stone's map and the E.R.T.S. imagery (Fig. 2), Township 28, Range 23; exists in the area of Mendota Heights. However, Gelineau's (1959) map and the E.R.T.S. imagery boundaries compare favorably here. Field checking showed that E.R.T.S. imagery boundaries were correct and Stone's interpretation was incorrect.

A third discrepancy arose in Burnsville (Fig. 2), Township 115, Range 21; where the boundary of Superior Lobe till of E.R.T.S. color-tone imagery extends into the Des Moines Lobe till of Stone's map. R. K. Hogberg (oral communication) notes that in this area, pockets of Superior Lobe till are incorporated with Des Moines Lobe till as indicated on Hogberg's (1970) map. These till pockets are responsible for producing the color tones observed on E.R.T.S. imagery. Thus, I extended the boundaries of Superior Lobe red till into the Des Moines Lobe buff-colored till.

The E.R.T.S. color-tone imagery boundary, south of Grey Cloud Island, fails to correctly delineate the boundaries of lithologic units. For example, the boundary that E.R.T.S. suggests is merely a geomorphic feature. The E.R.T.S. boundary in Mendota Heights is correct; Stone's (1965) map is incorrect. In the area of Burnsville, the

E.R.T.S. boundary is correct as is shown by the pockets of Superior Lobe red till lying within the boundaries of the Des Moines lobe buff-colored till.

A large discrepancy, that can be noted between E.R.T.S. color tone imagery and Stone (1965) is located in Township 27, Ranges 23 and 24. This discrepancy involves the location of the band of Des Moines Lobe outwash. E.R.T.S. color-tone imagery locates the band in different areas than do other geologic maps (e.g., Gelineau, 1959; Stone, 1965; Harms, et al., 1975). Each of the four maps mentioned above, locates the band in different areas. Moreover, the width of the band varies in each of the maps. The limits of time prevented field-checking of this problem, but the problem is such that a program of extensive field work should be initiated (see Fig. 4).

Study Area Two, in the New Brighton Quadrangle (Fig. 3), consists of lake sands and till deposits. Two geological reference maps, the New Brighton 7.5-minute Quadrangle (Stone, 1966), and a corrosion probability map (1974), served as a geological base. Stone's (1966) map was used as the geological base for the corrosion probability map. Extensive geophysical field work in the area showed Stone's (1966) map to be reliable. E.R.T.S. color-tone imagery in area two, showed that only a few areas were in close agreement with Stone's (1966) map. For the most part, the lithologic boundaries drawn from E.R.T.S. color tones exhibit major deviations from Stone's (1966) map. It is concluded that use of E.R.T.S. imagery in this area has limited usefulness for mapping lithologic units. Color-tone variations result from the high concentrations of housing developments, factories and highways, all located within the boundaries of this map. By comparison, Study Area One did not exhibit as dense a concentration of buildings and highways. The boundary discrepancy noted east and north of Round Lake is due chiefly to color tones produced by the Twin Cities Army Ammunition Plant and housing, not to lithologic changes. Similarly, the large boundary discrepancy north of lakes Johanna and Josephine is due to a heavy density of buildings. It appears that where concentrations of buildings occur, the use of E.R.T.S. as a geological mapping tool is not recommended.

This pilot project on the uses of E.R.T.S. as a major geological mapping tool has shown that in certain instances it can be helpful for mapping glacial geology, as demonstrated in Study Area One. It has also shown that there are limitations to the use of E.R.T.S. in areas where there are dense concentrations of buildings, as in Study Area Two. Additional investigations into E.R.T.S. should follow this preliminary study in order to more clearly identify the uses and limitations of E.R.T.S. as applied to geologic mapping. More studies should be initiated in areas of heavy urbanization and in regions where farm land predominates. The results of this metropolitan area E.R.T.S. study suggest that the technique might possibly be used as a reconnaissance tool for a state-wide project, but only if it were accompanied by extensive, detailed, field, geologic studies.

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___________, 1966, Surficial geology of the New Brighton Quadrangle Minnesota: Minn. Geol. Survey GM-2, 39 pp.

FIGURE 1

Reconnaissance Map of the surficial geology of the Minneapolis - St. Paul area

ORIGINAL PAGE IS OF POOR QUALITY

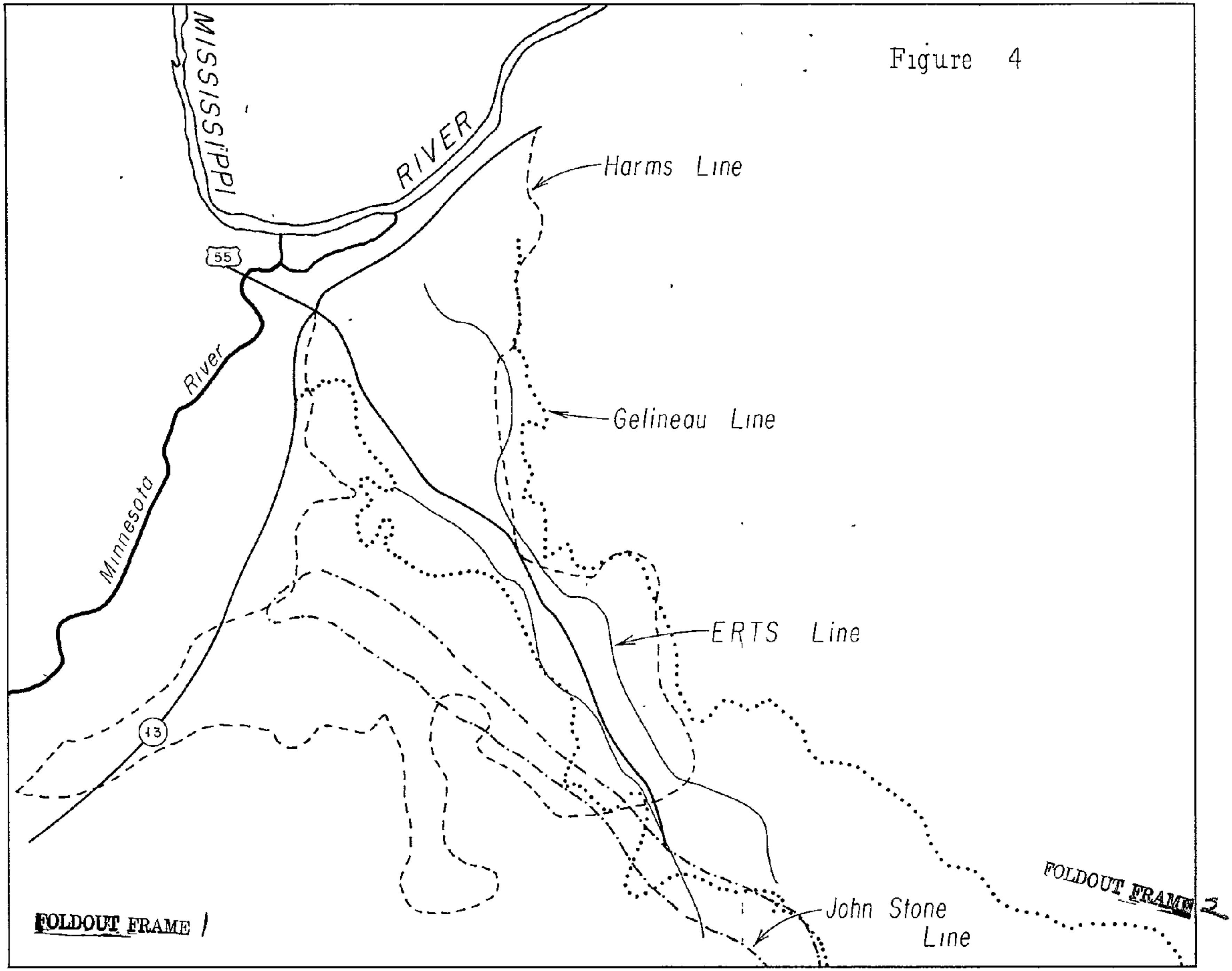
FOLDOUT 1

FOLDOUT 2

FIGURE 2

FIGURE 3

FIGURE 4



MINNESOTA GEOLOGICAL SURVEY
UNIVERSITY OF MINNESOTA
1633 EUSTIS ST.
ST. PAUL, MINNESOTA 55108

N76 14573

APPLICATIONS OF LANDSAT IMAGERY TO GEOLOGICAL RESEARCH IN MINNESOTA

Investigators: P. W. Weiblen, G. B. Morey, and M. S. Walton
Minnesota Geological Survey
St. Paul, Minnesota

In addition to the investigation of the applications of LANDSAT imagery to geology in the Twin Cities Metropolitan Area, the Minnesota Geological Survey has explored potential applications in other areas in Minnesota. Special attention has been paid to LANDSAT imagery covering a large part of northeastern Minnesota north of Lake Superior. The bedrock geology of this area has been a subject of long-standing scientific study, but it has recently excited new interest because it has been shown to expose a sequence of rocks which formed in an intercontinental rift about one billion years ago (fig. 1). In addition, the area is now under active exploration and preliminary development for large, low-grade copper-nickel deposits associated with the Duluth Complex, one of the major mafic igneous rock bodies of the United States (Appendix I). Consequently some of the major environmental issues involving land-use conflicts and pollution from mining operations affecting Minnesota are concentrated in this area. Geologic mapping of bedrock and surficial geology provides the basic data for a variety of federal and state studies now underway or proposed which pertain to these issues. At present only a small fraction of the copper-nickel target area has been mapped by the Minnesota Geological Survey (Appendix I, fig. 5, p. 91).

Northeastern Minnesota is heavily wooded, much of it is wilderness, and access to large areas is difficult. Mapping by conventional methods is both time-consuming and expensive. One quadrangle represents a minimum of one man-year of work and a cost of approximately $45,000, excluding publication. The completed mapping (Appendix I, fig. 5, p. 91) covers areas of relatively abundant exposures, but outcrops are still sporadic and interrupted by swamps, glacial deposits and lakes. Therefore the maps are based on considerable interpretation and extrapolation. We have found that by using LANDSAT imagery in conjunction with the available field data, it is possible to develop a much higher level of continuity and structural resolution in our interpretations of the bedrock geology. For example, Figure 2 shows the generalized geology of northeastern Minnesota as it was interpreted in January, 1975. It can be seen from Figures 3 and 4 that there is some correlation of linear and tonal features apparent on the LANDSAT imagery with the mapped geology (particularly the basal contact of the mineralized Duluth Complex). In other areas there is only a poor correlation between the presently mapped geology and the LANDSAT imagery. However, because of the extensive interpretation and extrapolation inherent in this geology, the LANDSAT imagery provides significantly new insights into critical target areas for further mapping and additional constraints on the interpretive aspects of the geology. For example, an analysis of the imagery (fig. 4) has revealed an area of structural complexity west of Grand Marais (fig. 2) which had not been detected by reconnaissance surface mapping. As discussed below, this is a critical area with regard to the overall genesis of the Duluth Complex rocks, and a field party is now investigating the area.

The preliminary results of our analysis of the correlation of the LANDSAT imagery with the surficial geology indicates that it is possible to distinguish various surficial morphological features such as the Vermilion and Highland moraines, the Toimi drumlin field, and an unnamed drumlin field apparently associated with the Highland moraine (fig. 5). The work suggests that major morphological features can be extrapolated from known areas into unknown areas by using the LANDSAT imagery. A knowledge of the overall distribution of these major morphological features is needed to aid in the detailed studies related to the various environmental impact statements being prepared by federal and state agencies and mining companies in the area of copper-nickel development.

The preliminary results of our analysis of the correlation of the LANDSAT imagery with the bedrock geology have significant consequences both in terms of evaluating the potential for copper-nickel resources in northeastern Minnesota and in understanding fundamental crustal processes (Appendix I, p. 83; Appendix II). This is true because the Duluth Complex is the surface manifestation of one of the major geological features of the North American continent, the so-called Midcontinent Gravity and Magnetic High (fig. 1). This feature, which extends in the subsurface from Lake Superior to southern Kansas, represents incipient rifting of the North American continent 1.1 billion years ago (fig. 1). Rifting was accompanied by the upwelling of vast quantities of mantle-derived magma capable of generating ore deposits (fig. 6), somewhat similar to the processes now going on along the mid-oceanic rifts (fig. 6; Appendix II). A better understanding of this rifting process, which is associated with the movement of major crustal plates, represents one of the most exciting and far-reaching advances in geologic thought in the last hundred years (Appendix II). An exceptional record of the processes associated with intracontinental rifting is recorded in the 1.1 billion year old rocks of northeastern Minnesota. Based on our present knowledge of these rocks, Weiblen and Morey (Appendix I) have developed a tectonic-petrologic model to account for the observed distribution of the Duluth Complex and associated rocks in a rift system. An integral part of their model is the recognition of the importance of faulting in the structural evolution of the area. The presently known copper-nickel resources are restricted to the basal contact zone of the Duluth Complex, and Weiblen and Morey (Appendix I) have shown that the mineralization is related at least in part to faults and fractures which transect both the older rocks and the Duluth Complex. The LANDSAT imagery in conjunction with other forms of imagery provide a means of better delineating the position of both the basal contact and the presence of faults and fractures (figs. 3 and 4). These data provide valuable constraints on selecting potential target sites for further economic evaluation (Appendix I, p. 84). Weiblen and Morey also have pointed out that mineralization need not be restricted to the base of the Complex but could occur throughout the rift system where the structural-magmatic setting of the basal zone might be repeated. For example, a copper-nickel deposit of economic importance has been found and is being developed in Canada seven kilometers north of the International boundary. This deposit is in an area where minor tabular bodies similar to the basal zone of the Duluth Complex occur, isolated from the complex proper. Similar occurrences have been prospected in Minnesota northeast of Grand Marais (fig. 2). Here, reconnaissance mapping has revealed only isolated exposures of potentially-mineralized rocks. The LANDSAT imagery, however, suggests that there may be a high density of rocks favorable for copper-nickel mineralization in the area. The LANDSAT imagery thus has delineated a specific area for detailed mapping that might otherwise have been ignored.

With regard to overall crustal processes we are now in the process of formulating a new concept of the fundamental crustal structure in Minnesota, and we have been aided by application of satellite imagery. Some of the results already have been embodied in five papers, cited below, which have been presented at recent scientific meetings and are now published or in press. We believe this work has important implications in better understanding global tectonic processes and also practical applications in defining targets for subsurface mineral exploration in the extensively drift-covered areas of the state.

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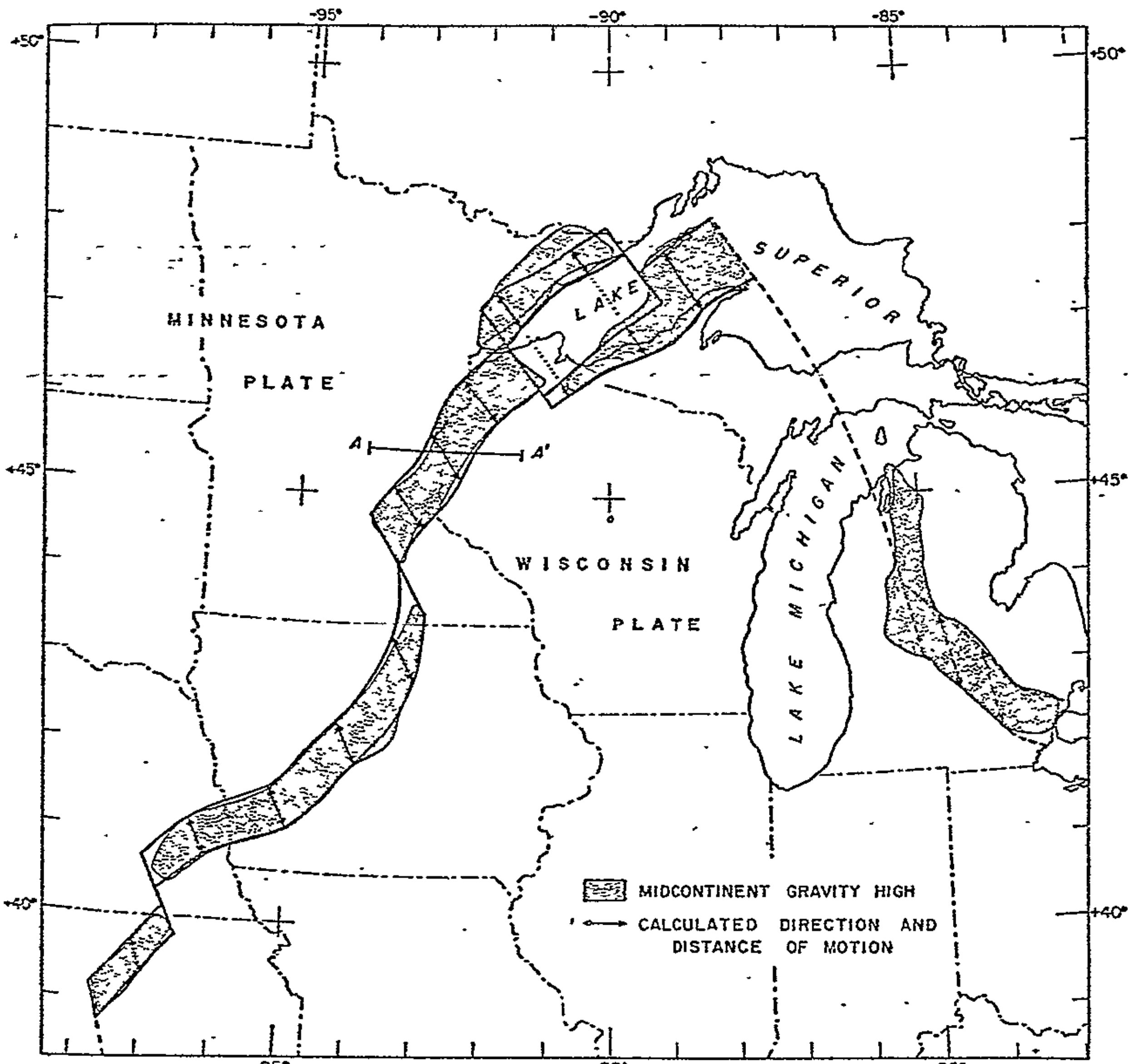

Plate tectonic geometry of the midcontinent gravity high, as predicted by the best-fit pole of relative rotation. The general agreement of offset trends and of width, except on the north shore of Lake Superior, is excellent. Dashed lines show possible extensions of the rift system, to the south at the western end, and into the Michigan Basin at the eastern end. The location of gravity profile A – A' (fig. 3) is also shown.

Figure 1. The Midcontinent rift from Chase and Gilmer (1973).

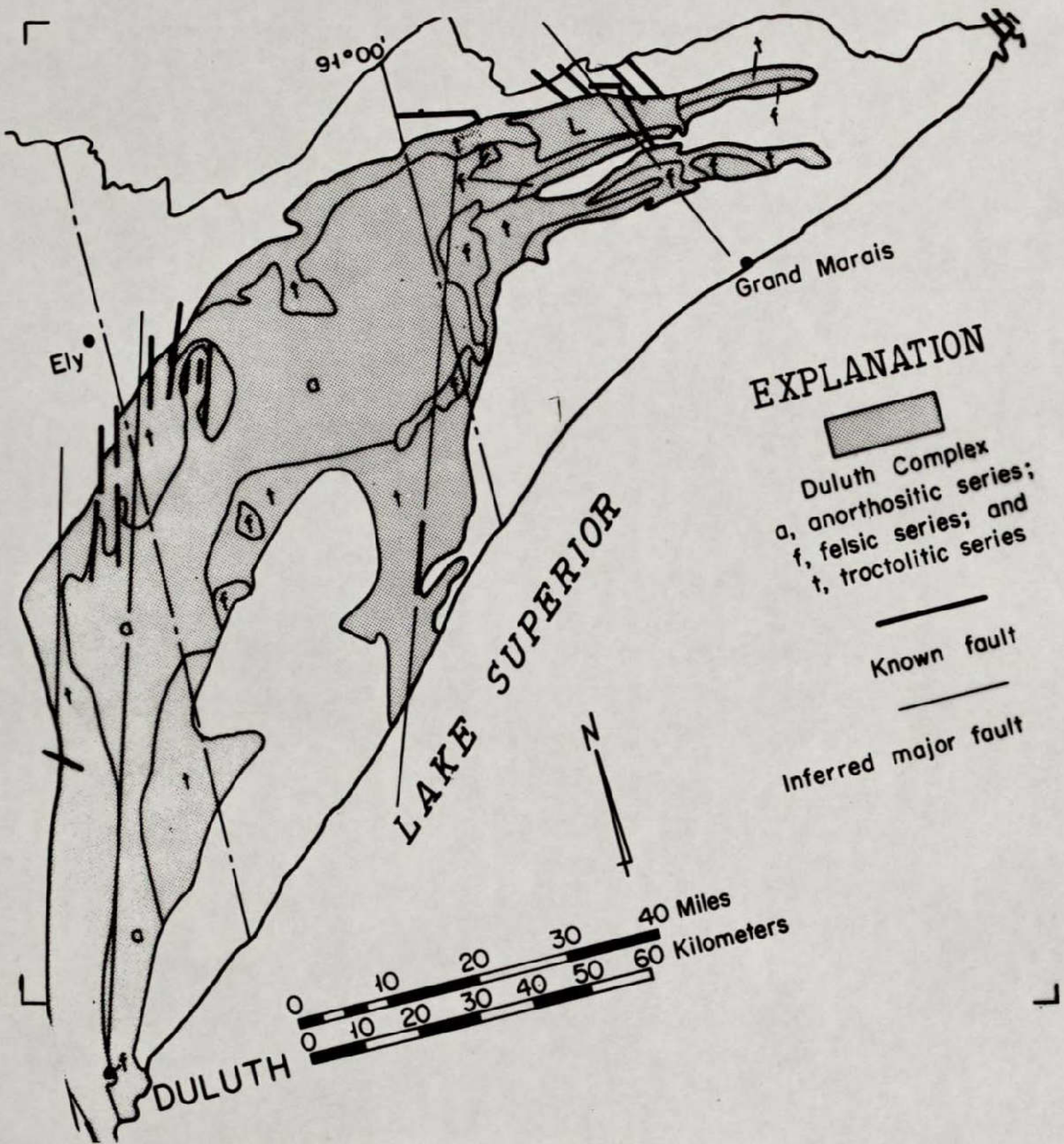

Figure 2. Generalized geologic of the Duluth Complex from Weiblen and Mcrey (1975). See Appendix I, Figure 11, p. 93 for discussion. The area delineated by the corner ticks corresponds to the area of the imagery in Figure 3. Known copper-nickel mineralization is restricted to the basal zone of the Duluth Complex in the Troctolitic series rocks (t). The active area of exploration and development is south of Ely in a highly faulted area. The faults are parallel to the major faults bounding the rift system shown in Figure 1.

Figure 3a. LANDSAT imagery. Color reproduction of band 5 imagery of northeastern Minnesota reduced from an approximately 1:250,000 print.

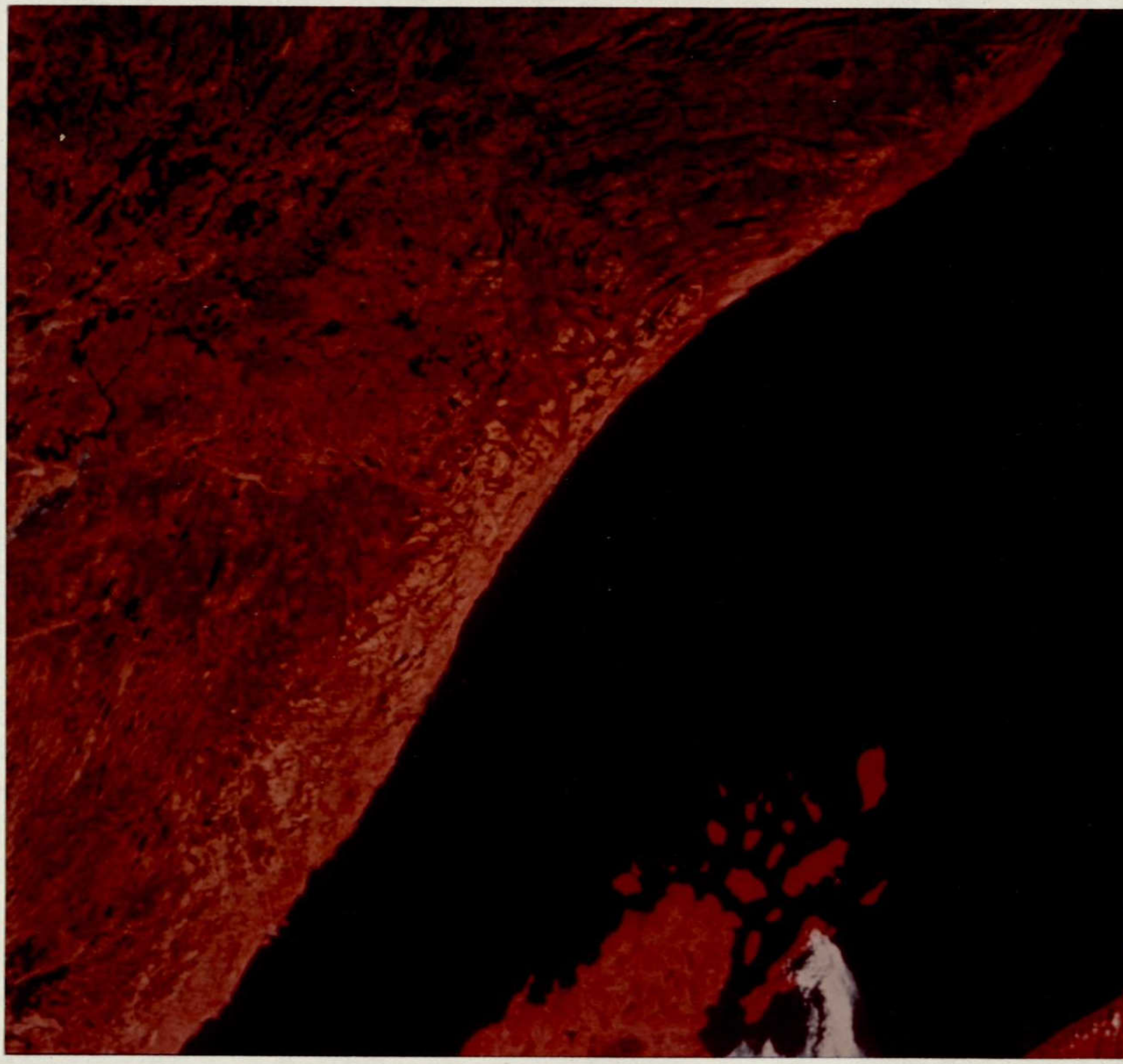

Figure 3b. Black and white negative print of Figure 3a.

Figure 4. [illegible] (Fig. 2). Solid light lines parallel the faults shown in Figure 1. In the area west of Grand Marais (Fig. 2) the density of linear features implies an area containing a large number of tabular bodies similar to those shown trending into Canada northeast of Grand Marais. See text for further discussion.

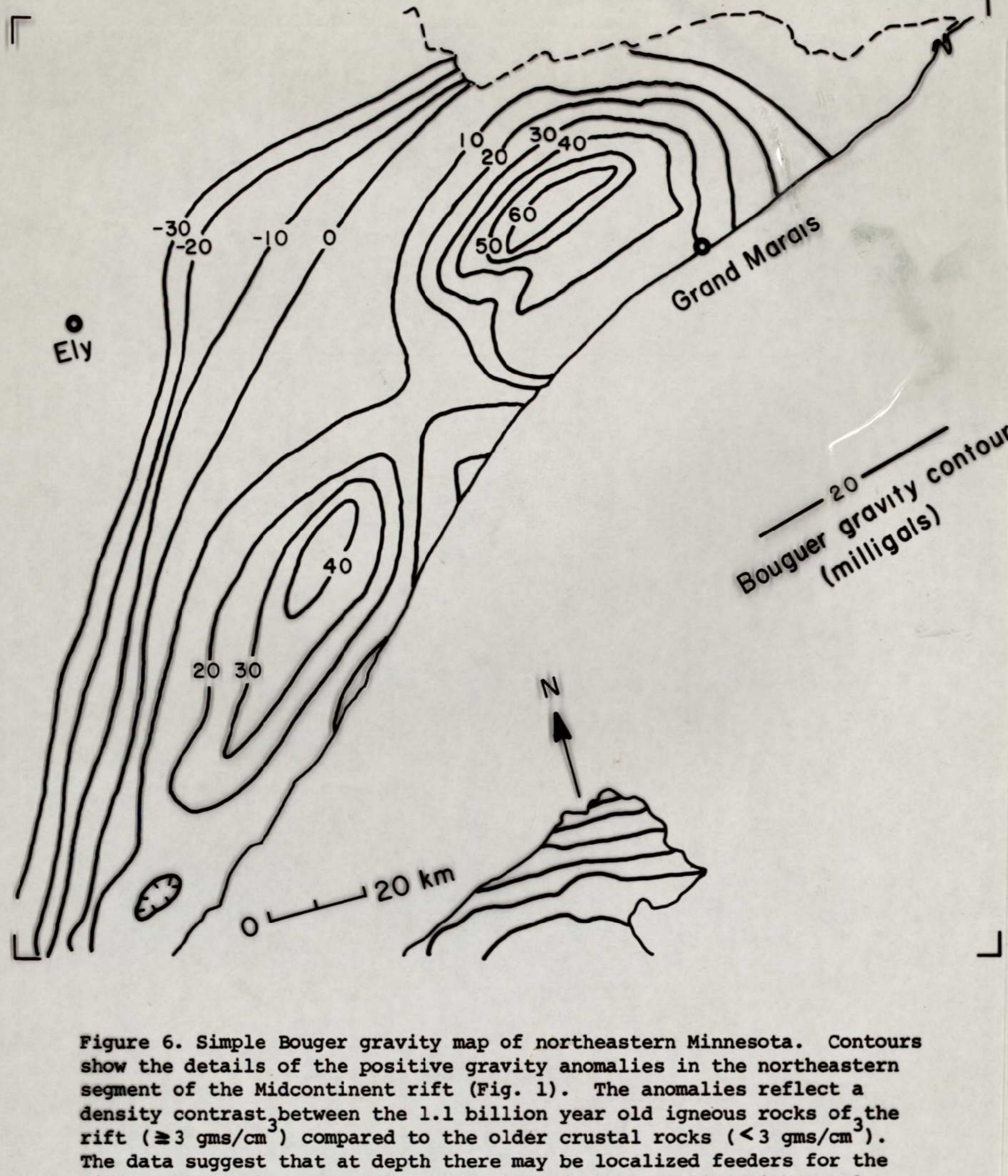

Figure 6. Simple Bouger gravity map of northeastern Minnesota. Contours show the details of the positive gravity anomalies in the northeastern segment of the Midcontinent rift (Fig. 1). The anomalies reflect a density contrast between the 1.1 billion year old igneous rocks of the rift (≥ 3 gms/cm^3) compared to the older crustal rocks (< 3 gms/cm^3). The data suggest that at depth there may be localized feeders for the rift system rocks. Partial correlation of the anomalies with tonal patterns in the LANDSAT imagery (Fig. 3b) is a reflection of the correlation of the geology with the gravity. Known areas of copper-nickel mineralization are restricted to the borders of the gravity anomalies but could occur throughout the rift. Modified from Graddock and others, 1969.

APPENDIX I

The Duluth Complex - A Petrologic and Tectonic Summary

Paul W. Weiblen and G. B. Morey

Minnesota Geological Survey

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THE DULUTH COMPLEX - A PETROLOGIC AND TECTONIC SUMMARY

Paul W. Weiblen *
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INTRODUCTION

The Duluth Complex, a large body of dominantly mafic igneous rocks of Late Precambrian (Keweenawan) age, is exposed sporadically along an arcuate belt extending from Duluth north toward Ely, and from there, east-northeast toward Hovland, Minnesota (Fig. 1). The complex is underlain to the west and north by older Precambrian rocks. The contact separating the older rocks from those of the Duluth Complex is generally sharp and well defined, and its position on various maps has not changed substantially as mapping has become more detailed (fig. 2). Because of a regional dip to the southeast, an extensive section of Keweenawan rocks (> 15 km thick, if a 12° dip is assumed) is exposed between the basal contact of the Duluth Complex and Lake Superior. The section contains in addition to the coarse-to fine-grained rocks of the complex proper, medium- to fine-grained, hypabyssal dikes and sills, and fine-grained, extrusive rocks of the North Shore Volcanic Group. This section represents a unique and rather complete exposure of a total magmatic system. Because the rock types in the upper part of the section are more or less gradational, the "upper" contact of the complex is an arbitrary boundary and its position on various maps has been continuously revised (fig. 2).

Although the Keweenawan rocks in northeastern Minnesota provide a dramatic view of a more or less complete magmatic system, they are only a small part of a much larger terrane that extends as a narrow linear belt as far south as southern Kansas. This structural feature, referred to as the Midcontinent Gravity High because of a large positive gravity signature, is interpretable within a framework of pre-Keweenawan tectonics (Weiblen and others, 1972-a), and Keweenawan rifting processes (Chase and Gilmer, 1973). Consequently, the petrogenetic and structural history of the complex must be considered within the constraints imposed by petrogenetic and tectonic processes in a rifting or tensional environment. As an initial attempt to view the available data on the Duluth Complex within these constraints, we present: (1) a summary of available field, petrographic, and petrochemical data pertinent to stratigraphic relationships within and between individual rock units of the complex; (2) a two-stage model of the igneous history of the complex based on the interpretation of the above data, in conjunction with additional data on the associated hypabyssal and extrusive rocks; (3) a systematic review of evidence for faulting in the complex; and (4) a tectonic model compatible with rifting processes which can account for the emplacement and present distribution of recognizable rock units within the Duluth Complex. An alphabetically arranged bibliography of all references to the Duluth Complex known to us at present is included at the end of this report. Additional general references cited are included in a separate bibliography.

GENERAL GEOLOGY

The Duluth Complex has been subdivided into a number of mappable units on the basis of textural and mineralogic attributes which generally are recognizable in outcrop (Grout, 1918b; Taylor, 1964; Phinney, 1969; Nathan, 1969; Weiblen and others, 1972; Bonnichsen, 1972; Davidson, 1972). Many of the distinctive textures that have been recognized are attributable to: (1) differences in grain size; (2) differences in mineral orientation and particularly in the orientation of plagioclase; and (3) the textural habit of plagioclase relative to that of other minerals, principally olivine, pyroxene, and iron-titanium oxides.

Differences in grain size, both within and between various rock units, have been expressed by various workers in different ways, but the classification scheme used by Nathan (1969) appears to be generally applicable throughout the Duluth Complex. Rocks having a grain size generally greater than 10 mm are referred to as very coarse-grained; 10-4 mm, coarse-grained; 4-1 mm, medium-grained; 1-0.5 mm, fine-grained; and less than 0.5 mm, very fine-grained. On this basis, most of the rocks in the Duluth Complex are coarse- or medium-grained. Very coarse-grained rocks generally are restricted to pegmatitic zones which occur as cross-cutting to concordant, cognate lenses within all other rock units. Fine-grained and very fine-grained rocks, on the other hand, are restricted mainly to inclusions of hornfels.

In most fine-grained rocks, tabular plagioclase grains are more or less randomly oriented, giving the rocks a massive appearance, but in coarser-

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grained rocks the plagioclase commonly has a preferred planar or linear orientation forming a foliated (e.g., Nathan, 1969, p. 33-34) or lineated (e.g., Weiblen, 1965, p. 89) fabric. Commonly rocks that are foliated or lineated are also layered, and the large-scale layers are defined by distinct differences in the relative proportions of various minerals. Such layering is presumed to have been formed by varying degrees of convection and crystal settling during crystallization of a magma (Grout, 1819 d and f; Wager and Brown, 1967, p. 1-7, Phinney, 1972, p. 341-342).

A specialized nomenclature has evolved to describe the kinds of layering and textures present in mafic rocks (e.g., Wager and Wadsworth, 1960; Wager and Brown, 1967, p. 65). This nomenclature in general implies interpretations of mode of origin and paragenesis. For example, the adjective "cumulus" is used to describe euhedral to subhedral minerals which are believed to have formed early, whereas "intercumulus" is used to describe anhedral and poikilitic minerals which crystallized late from melt interstitial to cumulus minerals.

In our review of textural descriptions of rocks in the Duluth Complex, we find that many rocks are described by terms having similar genetic implications (e.g., "fluxion structure," Grout, 1918b, p. 446, c; "primary" minerals, Weiblen, 1965, p. 75; Phinney, 1969, p. 8; and "cumulus" minerals, Nathan, 1969, p. 34). For this report we have attempted to separate textural descriptions from genetic interpretations. In so doing, we have found hat because plagioclase is relatively abundant (50-100%) in all rocks of the Duluth Complex, except peridotite and granophyre, its textural habit relative to that of other minerals provides a convenient criterion for classifying rock textures. Three broad textural categories have been recognized: (1) Tabular grains of plagioclase may form a simple framework within which other minerals such as olivine, pyroxene, and iron-titanium oxides occur as interstitial grains (2) Euhedral to subhedral grains of olivine may occur with tabular grains of plagioclase to form a more complex framework in which the other minerals occur as interstitial grains. The relatively simple textural characteristics of this and the first category are complicated by the fact that the proportion of interstitial material may vary considerably from sample to sample within a mappable unit. Moreover, the textural attributes of the interstitial material vary from situations where randomly oriented grains fill individual void spaces to situations where large optically continuous grains (oikocrysts) poikilitically enclose early formed, lath-shaped grains of plagioclase. (3) In certain suites of foliated rocks, a succession of textures commonly occurs in a stratigraphic succession which also defines the crystallization sequence. In a typical paragenetic sequence the textures of these rocks from early to late can be characterized by the successive appearance of euhedral to subhedral pyroxene, and iron-titanium oxides. Ideally the name can be assigned without regard to texture, but from a practical point of view, mineral abundances and textures are closely interrelated For example, most troctolitic rocks fall into textural categories 2 and 3. Consequently, through loose usage, the rock names themselves have taken on petrogenetic connotations. However, it is apparent from the various rock types illustrated in Figure 3 that texture is the primary attribute and controls in part relative mineral abundances. Thus, the textures and not the rock names are of primary petrogenetic significance.

Modern geologic mapping of the Duluth Complex using many of the above textural criteria for distinguishing rock types started in the late 1950's with the work of Taylor (1964) at Duluth. Since that time a total of twenty-six 7.5- and 15-minute quadrangles and five other miscellaneous maps have been prepared (fig. 5). Concurrent laboratory studies undertaken principally as graduate research projects have provided textural, modal, and analytical (electron microprobe and bulk chemical) data for the further characterization of rock units recognized during the mapping. The results of these mapping and laboratory studies in the Duluth Complex as well as data from mapping of the extrusive rocks along the north shore of Lake Superior and their associated hypabyssal rocks (Green, 1972) and mapping of the older Precambrian rocks and their associated Keweenawan hypabyssal rocks along the north edge of the Duluth Complex (Morey, 1972; Mudrey, 1970) have been compiled on a common base (fig. 6). This compilation highlights major gaps in the map coverage, but it also provides a new view of the spatial distribution of various rock types in the Duluth Complex. The data used for this compilation and the available results of laboratory studies are referenced, summarized and discussed below in terms of the six geographic areas shown in Figure 1. The interested reader is referred to the bibliography for more specific details and to Chapter V in Geology of Minnesota: A Centennial Volume (Sims and Morey, 1972) for another summary of the data available up to 1972.

DULUTH and VICINITY

Using the petrographic criteria discussed above, Taylor (1964) distinguished two major rock units at Duluth, which he termed "anorthositic gabbro" and a "layered" series. He also recognized three other rock units of limited areal extent: peridotite, ferrogranodiorite and granophyre. In as much as equivalents of these units have been found throughout the complex (Weiblen, 1965; Phinney, 1969; Davidson, 1969; Bonnichsen, 1972), we will use the more general terms "anorthositic series" and "troctolitic series" to refer to Taylor's two major units and the term "felsic series" as used by Davidson (1972) for ferrogranodiorite and granophyre.

Anorthositic Series

Taylor applied the name anorthositic gabbro to rocks having an average of 80 percent (range 50-100%) plagioclase. The plagioclase, generally of labradoritic composition, forms a framework of tabular grains characteristic of textural category 1 as defined above. Olivine, augite, and iron-titanium oxides occur interstitially to the plagioclase, suggesting that plagioclase was the first major phase to crystallize. The anorthositic rocks crop out at Duluth in a north-trending belt about one to three km wide. They are overlain by lava flows of the North Shore Volcanic Group (Green, 1972). Taylor (1964, p 9) found only two exposures of the actual contact and both reveal complicated contact relations. The flows appear to be recrystallized adjacent to the contact, implying that they were metamorphosed by the anorthositic rocks. However, no unequivocal chilled margin was found in the anorthositic rocks, and both coarse- and fine-grained rock types occur in the contact zone. The anorthositic rocks are underlain structurally by rocks of the troctolitic-gabbroic series. Again, the actual contact is exposed at only a few places, but Taylor, (1964, p. 9) concluded that the anorthositic series was older because a chilled margin was found in the troctolitic-gabbroic series at one locality, and because anorthositic rocks occur as inclusions in the troctolitic-gabbroic rocks The contact zone between anorthositic and troctolitic-gabbroic rocks, as mapped by Taylor, (1964, p. 11), also contains a series of cross-cutting dikes and irregular-shaped masses of granophyre.

No regular internal structure has been recognized in the anorthositic rocks at Duluth (Grout, 1917, p. 444; Taylor, 1964, p. 11). Rather, the unit has the appearance of an igneous breccia. Blocks with a consistent planar orientation of plagioclase and ranging in size from meters to tens of meters are randomly oriented with respect to one another and are set in a matrix of less well foliated anorthositic gabbro.

Neither Grout nor Taylor studied the anorthositic rocks in detail sufficient to establish the possible presence of systematic variations in mineralogy or mineral chemistry. The available compositional data are summarized and referenced in Tables 1 and 2, and Figures 7 and 8.

Troctolitic-Gabbroic Series

Troctolite, olivine gabbro, gabbro, and oxide gabbro (figs. 4a, b and 7) comprise more than two-thirds of the exposures at Duluth. In these rocks olivine, plagioclase, pyroxene, and iron-titanium oxides all occur as euhedral to subhedral grains with textural attributes similar to those characteristic of textural categories 2 and 3 defined above. Plagioclase generally is less abundant than in the anorthositic rocks, ranging from 17 to 81 percent (Taylor, 1964, p. 16).

Rocks assigned to the troctolitic-gabbroic series at Duluth are restricted to a 9.6 km wide north-trending unit sandwiched between an underlying sequence of lava flows and the overlying anorthositic rocks. The upper contact of the troctolitic-gabbroic with the anorthositic series has been described above. The lower contact of the troctolitic-gabbroic series with underlying lava flows is exposed only locally near Ely's Peak at the southwest end of the Duluth Complex (Taylor, 1964, p. 14). Here approximately 100 meters of magnetically reversed basaltic lava flows of the North Shore Volcanic Group (Kilburg, 1972) and about 500 meters of the troctolitic-gabbroic rocks are exposed in a one kilometer wide belt of nearly continuous outcrops along railcuts (Taylor, 1964, p. 11). The basaltic lava flows are re-crystallized (Kilburg, 1972, p. 73-87), but the precise location and nature of the contact remains poorly understood because of the presence of several other rock types in the contact zone. These include: (1) A 100 meter-wide zone of coarse-grained poikilitic, anorthositic troctolite which occurs immediately adjacent to the flows; (2) Isolated exposures of fine-grained mafic rocks which may be blocks of recrystallized basalt, chilled margin of the troctolitic-gabbroic series or possibly mafic dikes; (3) Dike-like masses, all less than a few tens of meters wide, of medium- to coarse-grained peridotite containing euhedral olivine, poikilitic pyroxene and interstitial ilmenite (Taylor, 1964, p. 29); and (4) A 50 meter-wide zone of coarse-grained anorthositic gabbro having interstitial augite altered to actinolite in immediate contact with the troctolitic-gabbroic series rocks. These contrasting rock types separate the lava flows from rocks definitely assignable to the troctolitic-gabbroic series by a distance of about 800 meters but none can be mapped along strike for more than a few kilometers and all have uncertain contact relationships with one another.

Taylor (1964) used the term "layered series" for the troctolitic-gabbroic rocks because locally mm to cm scale layers are found which are defined by rhythmic variations in the proportions of olivine, plagioclase, pyroxene, and oxide minerals (Taylor, 1964, p. 21, fig. 5). Planar orientation of elongate olivine and tabular grains of the latter three minerals imparts a foliation to these rocks which is parallel to the layering (Taylor, 1964, p. 22, fig. 6). The layering and foliation define a general north-northeast strike with dips ranging from 10 to 35 degrees to the east-southeast, but Taylor, (1964, p. 15) could not trace individual layers from one outcrop to another.

To look for systematic variations in mineral assemblages and compositions Taylor (1964, p. 15-28) examined in some detail a sequence of 20 samples along a transect parallel to the general dip direction. Three important characteristics of the troctolitic-gabbroic rocks can be deduced from his observations. First, the crystallization sequence in the layered series from earliest to latest is olivine, plagioclase, augite, and magnetite-ilmenite. Second, the various minerals exhibit a range in chemical compositions that can be correlated in a general way with differentiation of a magma by crystal fractionation (figs. 7 and 8; tables 1 and 2). Third, the chemical composition of the minerals does not vary systematically with stratigraphic position in the troctolitic-gabbroic series (Taylor, 1964, p. 23-25). The latter characteristic and the discontinuous nature of the layering support the view that the troctolitic-gabbroic rocks at Duluth did not form in a well developed, stable magma chamber under quiescent conditions like that inferred for many other layered intrusions. In the Skaerguard intrusion in Greenland for example, the systematic variations in mineral assemblages and compositions can be ascribed to a single stage of magma emplacement in a funnel-shaped magma chamber with loss of heat predominantly through the roof of the intrusion (Wager and Brown, 1969, p. 204 and 212). At Duluth, however, the geometry of the magma chamber, style of magma emplacement, and location of the cooling surfaces remain obscure. Undoubtedly, this is due in part to a lack of detailed data but it also is due to the complex nature of the upper and lower contacts and to ambiguities inherent in interpreting the structural significance of layering formed under turbulent conditions. The overall complexities presently recognized in the troctolitic-gabbroic series at Duluth are what might be expected if magma emplacement and cooling took place in a tectonically unstable environment.

Peridotite

Several isolated occurrences of peridotite were noted by Grout (1918e) and briefly described by Taylor (1964, p. 29) The best occurrence is that of a lens about 15 meters wide exposed in the contact zone between troctolitic-gabbroic rocks and basaltic lava flows at Ely's Peak (Taylor, 1964, Plate 1). Although the contact relations there and elsewhere are obscure, it appears that the peridotite extends along strike for about 1 kilometer. Much of the peridotite is highly altered to serpentine, chlorite, and talc, but samples of fresh rock contain euhedral olivine enclosed in a matrix of poikilitic augite and interstitial magnetite-ilmenite. Both chemical and mineral analyses are listed in Tables 1 and 2 respectively.

Felsic Series

Based on modal mineralogy, Taylor, (1964, p. 33-42) distinguished four intermediate to felsic rock types at Duluth These include ferrogranodiorite, adamelite, syneodiorite, and granophyre. All are characterized by significant amounts of quartz, potassium feldspar, iron-rich monoclinic pyroxene, amphibole (primarily hornblende) and titaniferous magnetite (Tables 1 and 2). The felsic rocks occur principally as irregular-shaped masses in the upper part of the anorthositic series, but several small bodies have been mapped along the contact between the anorthositic series and the troctolitic-gabbroic series (Taylor, 1964, Plate 1). Contacts between the felsic and anorthositic rocks as well as internal structures in the felsic rocks — as defined by changes in grain size, mineral proportions and textural attributes of the late formed minerals — may be either gradational or sharp. The origin of intermediate rock types having gradational contacts has been interpreted in two ways: (1) As an intermediate rock type formed during continuous differentiation of mafic to felsic rocks (Taylor, 1964, p. 9); or (2) as the product of a reaction between granophyre and older anorthositic or troctolitic rocks (Taylor, 1964, p 50). This apparent ambiguity is discussed further below (see also, Nathan, 1969, p. 152-155, 184; and Babcock, 1959).

Extrusive, Hypabyssal and Xenolithic Rocks

Extrusive Rocks: Stratigraphic and combined chemical and petrographic studies of the Keweenawan extrusive rocks by Green (1972) and Kilburg (1972) have provided critical data necessary for new petrogenetic interpretations of the Duluth Complex. These data will not be summarized here except to emphasize that there are important differences between the lava flows which underlie the Duluth Complex and those which overlie it (fig. 6). Rocks underlying the complex consist dominantly of a sequence of subaerial basalts having pyroxene phenocrysts and reversed remnant magnetic polarity, whereas, the overlying flows consist of plagioclase phenocryst-bearing basalt flows which are complexly intercalated with flows having rhyolitic to intermediate compositions and with interflow sedimentary rocks. The latter sequence consistently has a normal remnant magnetic polarity. Further, whole-rock chemical analyses (Green, 1972) summarized in Table 3 show that the two flow sequences have distinctly different major element compositions. The significance of these differences to the petrogenesis of the Duluth Complex is discussed further below, but the overall differences together with the stratigraphic relations suggest that the upper flows could be part of a magmatic episode which is distinct and later than that responsible for the lower flows.

Hypabyssal Rocks: Hypabyssal dike rocks at Duluth range in thickness from a few meters to several tens of meters, and in grain size from basalt to diabase (microgabbro). All of the dikes trend generally northward, but the dikes cutting pyroxene phenocryst-bearing lava flows at Ely's peak trend east of north, whereas those dikes cutting anorthositic series rocks and plagioclase phenocryst-bearing lava flows trend west of north. Stratigraphic and compositional variations in most of these have not been studied in detail, but several dikes that have been analyzed have a whole rock chemical composition similar to that of the Logan intrusions, which intrude the Rove and Gunflint Formations in the Gunflint Corridor of Cook County (fig. 5).

Several sill-like bodies of hypabyssal rocks also are exposed at Duluth. The largest of these, the so-called "Endion Sill" has been studied in greatest detail (Schwartz and Sandberg, 1940; Ernst, 1960; Taylor, 1964, p. 11). It is a north-trending, kilometer-wide body of differentiated micro-gabbro that intrudes rocks of the anorthositic series, felsic series and the North Shore Volcanic Group in the eastern part of Duluth (fig. 4). Although the sill has been referred to as "olivine gabbro" by Green (1972), it contains only minor amounts of olivine and appears to have a Logan composition (Ernst, 1960, Table 3).

Xenoliths: The recognition of xenolithic inclusions in different units of the Duluth Complex is somewhat subjective because of incomplete exposures and because we do not know the entire spectrum of modal and textural attributes associated with either the xenoliths or with the rock units described above. In general, two kinds of xenoliths are recognized: (1) feldspar-rich rocks having textural and modal characteristics similar to those of anorthositic series rocks; and (2) a variety of fine-grained gabbroic rocks having hornfelsic or granoblastic textures. The anorthositic xenoliths occur more or less randomly in the troctolitic-gabbroic series where they range in size from several millimeters to 500 meters (Taylor, 1964, plate 11). Judged from their textural and mineralogical attributes, these xenoliths were derived from rocks of anorthositic series.

Xenoliths of fine-grained hornfels exhibit a range of sizes similar to that of the feldspathic xenoliths, but their spatial distribution differs in that they tend to be concentrated near the margins of the troctolitic-gabbroic series. Many of these xenoliths may be contact metamorphosed basalt flows as suggested by Schwartz (1949, p. 90), but other xenoliths may be fragments of chilled margin facies of the coarse-grained rocks (Taylor, 1964, p. 13) or fragments of hypabyssal rocks which were intruded in the anorthositic series rocks and which subsequently were broken up when parts of this series were incorporated in the troctolitic-gabbroic magma. The range of contrasting chemical compositions has not been studied in detail, but Goldich (1971) has shown that one possible xenolith at Duluth has a composition very similar to that of a lunar mare basalt (Table 1).

DULUTH TO HOYT LAKES AREA

Bonnichsen (1971) has prepared a compilation of the known exposures between Duluth and the Hoyt Lakes area (fig. 1) based on previous data and one field season of reconnaissance mapping. The exposures are isolated and all are less than a kilometer in size. Consequently, our knowledge of the Duluth Complex in this area depends largely on geophysical data supplemented by drilling. The complex throughout much of the area dips toward the east and is bounded on the west by Middle Precambrian strata and locally by basaltic hornfels too small to be shown on Figure 6. The complex is bounded to the east by magnetically normal lava flows of the North Shore Volcanic Group and associated dikes and sills (Green, 1972).

Both anorthositic and troctolitic-gabbroic rocks like those exposed at Duluth have been recognized, and as at Duluth, the troctolitic-gabbroic rocks form a north-northeast-trending belt which appears to be overlain by the anorthositic rocks. However, the exposures are too limited to extrapolate with certainty the thickness and continuity of each series or textural and compositional variations within each series.

Bonnichsen (1972) has briefly described a tabular or lens-shaped body of peridotite about 400 meters long and 200 meters thick which was discovered by drilling in an area about 30 km north of Duluth. Basal rocks consist of olivine, pyroxene, and ilmenite, they grade upward into plagioclase-bearing peridotite and gabbro. The peridotite dips steeply to the east and overlies a basaltic hornfels which is compositionally similar to the pyroxene phenocryst-bearing flows at Duluth. (Bonnichsen, 1972, p. 387). Bonnichsen (1972, p. 373) reports that the peridotite is overlain by olivine gabbro. Textures (fig. 3), whole-rock, and mineral compositions (figs. 7, 8, Tables 1 and 2) are similar to those in the peridotite exposed at Duluth and in the Water Hen Creek intrusion.

The Water Hen Creek intrusion has been described from drill core by Mainwaring and Naldrett (1974, 1975). It is a relatively small body that has the shape of a moderately-to steeply-dipping, somewhat flattened cylinder with a very thin lip forming the westernmost extremity. It is in contact to the west with Middle Precambrian metasedimentary rocks and to the east with rocks of the troctolitic-gabbroic series. Dunite (Fo = 65-55%) occurs as a basal unit and is overlain by repetitive layers of peridotite, ilmenite peridotite, troctolite, and minor anorthosite. Marginal facies are complicated; they are rich in inclusions and there is little evidence of chilling or recrystallization. Abundant interstitial sulfides occur in the dunites, whereas they are virtually absent in the more feldspathic rocks.

Although the peridotitic rocks are not well exposed or delineated, it appears that they occur as small, discontinuous bodies aligned more or less parallel to the basal contact of the Duluth Complex. Because the bedrock is mantled by a thick cover of Pleistocene materials, the actual extent of peridotite is unknown, but it could conceivably be much greater than presently recognized. The significance of these peridotite bodies is discussed below in connection with the petrogenetic model that will be outlined.

Isolated exposures of hornfels and felsic series rocks occur within the Duluth Complex well away from the basal zone, completing in this area the same spectrum of rock types as found at Duluth.

HOYT LAKES–KAWISHIWI AREA

Detailed mapping by Green and others (1966) and associated petrographic studies by Phinney (1969) and Weiblen (1965) in the Gabbro Lake quadrangle at the east end of the Hoyt Lakes-Kawishiwi areas (figs. 1, 5, and 6) has documented the presence of anorthositic and troctolitic-gabbroic rocks similar to those exposed at Duluth. However, in this area, several varieties of anorthositic rocks may be distinguished on the basis of subtle differences in mineralogy and texture. They include poikilitic gabbroic anorthosite, noritic anorthosite, and oxide-rich anorthosite (Phinney, 1969, p. 6-10). Although the different varieties can be traced over distances greater than several kilometers, contacts are vague and irregular. As at Duluth, the orientations of the plagioclase lamination is not consistent over distances greater than several tens of meters, and the different varieties are found as blocks a few meters across in other units, making Taylor's term "igneous breccia" an apt descriptor of the anorthositic series in this area.

Rocks texturally and mineralogically similar to the troctolitic-gabbroic series at Duluth occur as three distinct intrusive units in the Gabbro Lake quadrangle. These include:

(1) The Bald Eagle intrusion, a three by ten km, funnel-shaped body consisting of two distinct rock types, an outer zone of troctolite and an inner core of olivine gabbro. The intrusion has well defined intrusive contacts where it cuts rocks of the anorthositic series (see Figure 1, Weiblen and Perry, in prep. and Weiblen, 1965). Mineral layering and lamination are well developed and the intrusion also exhibits systematic variations in mineral compositions (fig. 8). A conspicuous lack of interstitial material, similar to that illustrated in Figure 3, indicates that flow predomiated over gravity segregation in the development of the layering in these rocks.

(2) A second troctolitic-gabbroic unit, the South Kawishiwi intrusion, occurs at the base of the Duluth Complex in the southwest part of the Gabbro Lake quadrangle. It is in contact to the north and west with older Precambrian rocks, and to the east it either intrudes or is in fault contact with rocks of the anorthositic series. The southern or upper contact is obscured by glacial drift. The possible southwestward extension of this intrusion across the entire Hoyt Lakes-Kawishiwi area is discussed below.

The South Kawishiwi intrusion is divisible into at least three units on the basis of differences in mineralogy and texture. They are, from bottom to top: (1) a contact zone, (2) an augite-bearing troctolite unit, and (3) an upper troctolite unit. Layering due to gravity segregation of olivine and plagioclase is well-developed in the upper unit, less well-developed in the augite-troctolite unit, and absent in the basal contact zone. Inclusions are found in much greater variety in the South Kawishiwi intrusion than are recognized in the troctolitic-gabbroic rocks at Duluth. They include mappable units of several kinds of anorthositic rocks, iron-formation, metasedimentary and basalt hornfels The inclusions are most abundant in the contact zone, but they also are present in the augite troctolite. Sulfide mineralization of importance in this part of the Duluth Complex is restricted to the contact zone. This aspect of the intrusion is the subject of an accompanying report in this volume by Weiblen and Perry.

(3) The Bald Eagle and the South Kawishiwi intrusions appear to be connected by a dike-like intrusion of troctolitic-gabbroic rock that is approximately one-half kilometer wide and three kilometers long (Phinney, 1969, p 13-14). This intrusion consists of an outer zone of interlayered troctolite and olivine gabbro and an inner zone of pegmatitic gabbro having plagioclase and pyroxene crystals as much as 10 cm long. It also includes several kinds of hornfels inclusions. The relationships of the different rock types in this intrusion have not been studied in any

detail, but it has been proposed that the Bald Eagle intrusion was a feeder for the troctolitic-gabbroic rocks to the southwest and that this dike-like intrusion is a part of the feeder system (Weiblen, 1965; Phinney, 1972).

No bodies of peridotite have been found in the Gabbro Lake quadrangle, but other minor intrusions include several possible extensions of the Bald Eagle intrusion between it and the South Kawishiwi intrusion (Green and others, 1969) and a few small exposures of granophyre. The latter occur as dike-like masses, generally less than a meter wide, along north-northeast trending cataclastic zones that cut both the anorthositic and troctolitic rocks However, the known occurrences of granophyre are restricted to cataclastic zones in anorthositic rocks. These occurrences of granophyre imply that igneous activity and tectonism were at least partly contemporaneous. The tectonic significance of the cataclastic zones is discussed further below in conjunction with evidence of faulting in the Duluth Complex.

Detailed and reconnaissance mapping by Bonnichsen (1972) in the Greenwood Lake, Kangas Bay, Babbitt, Babbitt N.E., Babbitt S.E., Babbitt S.W. and Allen quadrangles has extended the known limits of troctolitic-gabbroic rocks similar to those of the South Kawishiwi intrusion across the entire Hoyt Lakes-Kawishiwi area, and has confirmed the presence of complex contact zone rocks along the base of the complex throughout the area Bonnichsen's mapping also has confirmed the presence of anorthositic series inclusions throughout the troctolitic-gabbroic series. The three-fold stratigraphic succession recognized in the South Kawishiwi intrusion has not been traced into the quadrangles mapped by Bonnichsen, and it appears that the troctolitic-gabbroic rocks are interrupted by north-northeast trending belts of anorthositic rocks (fig 6). Thus, it is not entirely clear that the troctolitic-gabbroic series rocks in the Hoyt Lakes-Kawishiwi area are all part of one intrusion.

Isolated exposures of an oxide-rich gabbro occur in the south half of the Greenwood Lake quadrangle The texture and mineral composition of these rocks are similar to those expected for further differentiates of the Bald Eagle intrusion (Weiblen, 1965; Bonnichsen, 1972). Significant masses of granophyre also occur in this part of the Hoyt Lakes-Kawishiwi area (fig. 6).

BOUNDARY WATERS CANOE AREA

Reconnaissance mapping in the Boundary Waters Canoe Area (B.W C.A) (fig. 1) and quadrangle mapping in the Gillis Lake quadrangle (fig 5) (Beitsch, in prep) indicates a general continuation of the rock units and field relationships described in the Hoyt Lakes-Kawishiwi area However, the geologic relationships are complicated in the southeast part of the B.W C A (figs. 1 and 6) by the presence of extensive masses of felsic series rocks and basaltic hornfels.

These rocks, as well as the anorthositic and troctolitic-gabbroic rocks in the Brule River prong, have been mapped in thirteen 7 ½-minute quadrangles (fig. 5) by Davidson (1972) This work has led to the preliminary characterization of the various hornfelsic and felsic rocks and has provided information on their stratigraphic position Because of excellent and extensive exposures, particularly along lake shores, this area has the potential of eventually providing the best geologic control on stratigraphic and structural relations of the late differentiates in the complex, as well as a complete spectrum of critical samples needed to refine petrogenetic and structural models for the complex as a whole. Representative data on analyzed samples from the different rock units studied in the B.W.C.A. are included in Tables 1 and 2 and Figures 7 and 8.

GUNFLINT CORRIDOR

The Gunflint Corridor (fig 1) can conveniently be divided into three geographic areas, each with distinctive geology: (1) the Long Island Lake quadrangle, (2) Northern prong, and (3) Brule River prong. Recent mapping in the Long Island Lake quadrangle by Weiblen (Morey and others, 1969) demonstrated the presence of a sequence of rocks similar to those in the Duluth Complex at Duluth. To the east in the Gunflint Lake quadrangle, these rocks truncate an older series of interlayered anorthositic and troctolitic-gabbroic rocks which comprise the so-called Northern prong of the Duluth Complex. The interlayered anorthositic and troctolitic-gabbroic rocks, extend eastward across the southern parts of the South Lake and Hungry Jack Lake quadrangles (fig. 3), where they are truncated by large masses of differentiated felsic series rocks. The layered series rocks have been mapped in detail by Nathan (1969) and the felsic series rocks have been studied by Babcock (1959). The Brule River prong consists of a series of east-trending rocks which lie to the south of the rocks of the Northern prong and are separated from them by lava flows of the North Shore Volcanic Group. These rocks have been mapped by Davidson (1972) (fig 5).

Long Island Lake Quadrangle

Anorthositic Series: Anorthositic rocks having 75-95% plagioclase overlie a structurally lower sequence of troctolitic-gabbroic series rocks in the Long Island Lake quadrangle (Morey and others, 1969) The contact trends generally eastward and is concordant with layering in the underlying troctolitic-gabbroic rocks. The contact is marked by isolated masses of basaltic hornfels and by the presence of sulfide gossens in the troctolitic-gabbroic rocks However, the contact relationships are not straight forward because no chilled margin material has been found in the troctolitic-gabbroic rocks and because gabbroic anorthosite is inter-layered with poikilitic augite troctolite immediately adjacent to the contact. The anorthositic rocks south of this contact zone are predominantly gabbroic anorthosites characterized by a coarse-grain size and randomly oriented plagioclase foliation patterns, this fabric contrasts markedly with the more regularly developed foliation in the gabbroic anorthosite layers in the underlying troctolitic-gabbroic rocks. We infer, therefore, that all of the gabbroic anorthosites south of the contact are part of the older anorthositic series rocks mapped to the west by Phinney (1972) and Beitsch (in prep.).

In the southwest corner of the Long Island Lake quadrangle, the anorthositic rocks are cut by plug-like intrusions of felsic rocks, having an inner core of granophyre and an outer rim of ferrogranodiorite and anorthositic rocks are gradational and the origin of the intermediate rocks presents the same unresolved problems as at Duluth.

Troctolitic-Gabbroic Series: In the Long Island Lake quadrangle, a sequence of troctolitic-gabbroic rocks similar to those found elsewhere in the complex appears in the following succession away from the base: (1) fine-grained poikilitic augite troctolite, (2) fine-grained granoblastic gabbro (hornfels), (3) fine- to medium-grained troctolite, (4) medium- to coarse-grained troctolite, and (5) inter-layered troctolite and poikilitic augite troctolite.

These units have been referred to collectively as the Tuscarora intrusion (Weiblen and others, 1972). The Tuscarora intrusion consists dominantly of unit 4, having 65 to 70 percent plagioclase and 10 to 15 percent olivine. The relative amounts of other minerals such as poikilitic augite and iron-titanium oxides vary locally. Orthopyroxene mantles olivine and occurs in symplectic intergrowth with plagioclase. Biotite is associated with the iron-titanium oxides. The plagioclase exhibits a planar orientation and modal-mineral layering is locally well developed and mutually concordant as in the South Kawishiwi intrusion.

The medium- to coarse-grained troctolite of unit 4 becomes finer-grained toward the base, the grain size being roughly half of that of the overlying medium- to coarse-grained troctolite. This lower unit contains augite and copper-nickel sulfides which assay up to five-tenths of a percent copper plus nickel (Johnson, 1970).

The medium- to coarse-grained troctolite grades upward into a unit consisting of troctolite interlayered poikilitic augite troctolite. The troctolite within the interlayered interval is similar to that in unit 4 whereas the poikilitic augite troctolite contains about 70 percent plagioclase, 15 to 20 percent augite, and 5 to 10 percent ilmenite; it is medium- to coarse-grained and has well developed augite oikocrysts as much as 2 to 3 cm across. Contacts between layers are generally sharp and conformable to layering in the medium- to coarse-grained troctolite. The layering is nearly flat-lying on a large scale, but is undulatory on a small scale. Individual folds have wave lengths of 3 to 10 meters and amplitudes of one to three meters.

Gabbroic anorthosite layers as described above are developed in the upper part of this unit, and we consider them to be part of the Tuscarora intrusion

Fine-grained poikilitic augite troctolite occurs beneath the fine- to medium-grained troctolite (unit 1) (fig. 9). This unit contains 60 to 70 percent plagioclase, 5 to 10 percent olivine, 15 to 20 percent poikilitic augite, 5 to 10 percent iron-titanium oxide, and minor amounts of orthopyroxene-plagioclase symplectite. The contact between this unit and the sulfide-bearing zone in unit 4 troctolite is not exposed and it is not clear from surface mapping if it is a separate intrusion or the basal part of unit 4. Johnson (1970, p. 76) concluded from drill core data that it is a separate intrusion.

Granoblastic gabbro (unit 2) occurs in several kilometer size exposures as topographic highs which cap the fine- to medium-grained and medium- to coarse-grained troctolite in the Long Island Lake quadrangle (Morey and others, 1969). This rock consists of 50-60 percent short, tabular plagioclase, 30-40 percent rounded augite, and minor amounts of subhedral iron-titanium oxides, olivine, and biotite. These rocks have a horizontal foliation and minor mineral layering. They may be remnants of metamorphosed flows which once roofed the troctolite, but the troctolite is not noticeably finer-grained adjacent to the granoblastic gabbro. Consequently, the granoblastic rocks most likely are large inclusions.

Felsic Rock Units Associated with the Tuscarora Intrusion: Ferrogranodiorite and granophyre have intruded rocks of the anorthositic series in the southwest corner of the Long Island Lake quadrangle (fig. 6). The ferrogranodiorite grades into and is cut by fine- to medium-grained granophyre. The granophyre consists of quartz, plagioclase, potassium feldspar, and magnetite and textures range from granophyric to granitoid. The ferrogranodiorite is medium-grained and contains 50 to 60 percent plagioclase, 10 to 15 percent amphibole, minor clinopyroxene, and variable amounts of quartz, potassium feldspar, and magnetite.

It is not clear from the field relations if these rocks are related genetically to the troctolitic-gabbroic series, to the anorthositic series, or to either of them. Further study is needed to clarify the stratigraphic relationships.

Layered Series of Nathan: Nathan (1969) mapped in the Gunflint Lake, South Lake, and Hungry Jack Lake quadrangles (fig. 5 and 6), a series of sheet-like intrusions which comprise the central part of the Northern prong of the Duluth Complex (fig. 1). To the west, this layered series is truncated by the Tuscarora intrusion and its associated rocks; the contact is marked by an irregular, but generally northwest-trending lineament (fig. 9). To the east the layered series is truncated by rocks of the felsic series discussed below.

The layered series consists of a sequence of conformable sheets having a regional dip of 15-25° to the south. The sheets thicken to the west and are locally interrupted by minor cross-cutting stock- and dike-like bodies. On the east side of the Hungry Jack Lake quadrangle near Poplar Lake, a northwest-trending fault offsets the series with an unknown amount of displacement, but as much as 140 feet of vertical displacement of the northeast side is inferred (fig. 6).

Nathan (1969) recognized 27 different units. For the most part, they consist of troctolitic, gabbroic, and associated felsic rocks, but several of the major units represent occurrences unique in terms of abundance of oxide-rich gabbro and two-pyroxene gabbro. Generally, fine-grained rocks do not represent the chilled margins of large bodies, but occur as separate intrusions or inclusions of mappable size. Planar orientation of minerals is common, indicating flow or crystal settling. Differentiation resulting from these processes can be demonstrated within some units, but the layered series as a whole does not form a regular stratigraphic sequence.

Intrusive relationships between different units were established using cross-cutting structures, fine-grained margins, inclusions, and thermal effects, the latter being principally a development of dark-clouded plagioclase near intrusive contacts (Nathan, 1969, p. 99). On the basis of field relationships, mineralogy and composition, Nathan concluded that the 27 units could be combined into eight cogenetic groups.

Two summaries of Nathan's studies are available: Phinney, (1972) and Weiblen and others (1972). Mineral compositional variations are summarized in Figure 8.

Rocks of the Felsic Series at the East End of the Northern Prong: Intrusions of several kinds of felsic rocks (Babcock, 1959, Phinney, 1972) truncate the east end of Nathan's layered series (fig. 6). The genetic relationship of these rocks to units of the layered series is not clear but Nathan (1969) attributes the extensive occurrence of interstitial granophyre, the development of hornblende, and the sericitization of plagioclase in the layered rocks to alteration by a younger differentiated magma.

No detailed mapping has been done in the eastern end of the Northern prong, but samples from four traverses were described by Babcock (1959, 1960). Te recognized two distinctly different units· (1) a lower unit of undivided gabbroic rocks having variable amounts of interstitial granophyre, and (2) an upper felsic unit consisting essentially of granophyre with inclusions of gabbro and intermediate rock. Babcock concluded that the two units were genetically related. He envisioned that the gabbroic rocks formed by the early crystallization and accumulation of plagioclase and pyroxene in the lower part of a magma chamber, and that the interstitial felsic material was entrapped as crystallization proceeded. He considered the upper unit of predominantly felsic rocks to be the product of continued differentiation.

Cumulus plagioclase cores are more sodic (An45-55) than those of typical gabbroic rocks (An50-70) in other parts of the complex (fig. 8) This suggests that the initial magma was relatively differentiated at the time it was emplaced. This could account for the extensive occurrence of interstitial granophyre in the lower unit and the large volume of granophyre in the upper unit. More detailed studies are needed to establish the genetic relationship between the differentiated rocks of the felsic series and the mapped units of the anorthositic and troctolitic-gabbroic series rocks.

Brule River Prong: Reconnaissance mapping by Grout and others (1959) and Davidson (1972 and in prep.) in the Sawbill Camp, Brule Lake, Eagle Mountain, Lima Mountain, Pine Mountain and Northern Light Lake quadrangles (fig. 5) indicates that there is a general similarity in rock types at the east end of the Northern prong and in the Brule River prong (fig. 6). The Brule River prong consists dominantly of a lower olivine gabbro unit and an upper felsic unit. This simple picture is complicated by discontinuities in the general eastward-trend of the contact between the two units and by variations in mineralogy and textures within the units As in the Northern prong, it is not clear from field observations and petrographic and chemical data (Davidson, 1972) whether or not the olivine gabbro is an extension of the troctolitic-gabbroic series in the Long Island Lake quadrangle, a repetition of some of Nathan's layered series units or a separate intrusion. Both gradational and sharp contact relationships occur between felsic rocks and the olivine gabbro; and thus the felsic rocks present the same problem as elsewhere in the complex. Because the rocks of the Brule River prong are a more or less self-contained entity within the North Shore Volcanic Group, they are a prime target for additional field, petrographic, and chemical studies to evaluate the petrogenetic and tectonic models of the complex developed in this report.

FINLAND-BEAVER BAY AREA

Recent mapping in the Finland area (Stevenson, 1973) has delineated a body of troctolitic-gabbroic rock which intrudes lava flows of the North Shore Volcanic Group. This intrusion, named the Sonju Lake intrusion, is characterized by well-developed plagioclase foliation, and igneous layering. The intrusion consists of several mappable units which include from base to top: picrite, troctolite, gabbro, ferrogabbro, granodiorite, and adamellite. As such the Sonju Lake intrusion is the best exposed and most completely and systematically differentiated intrusion in the troctolitic-gabbroic series (Tables 1 and 2, figs. 7 and 8)

South of Finland, near Beaver Bay on the shore of Lake Superior, a sequence of layered iron-rich gabbroic and diabasic rocks also intrudes the flows of the North Shore Volcanic Group. These rocks, referred to as the Beaver Bay Complex (Gehman, 1956), exhibit a differentiation trend similar to that observed in the Sonju Lake intrusion. The main unit at Beaver Bay is a sill-like body of medium- to coarse-grained olivine gabbro. Elliptical plugs of ferrogabbro, one to two km in diameter cut this main unit. The ferrogabbros have a well-developed mineral foliation. Interstitial granophyre is a locally significant component of both the olivine gabbro and the ferrogabbro, and intrusions of various kinds of granophyric rock occur throughout the area.

Aside from their location (fig. 6), there is no compelling reason to exclude from the Duluth Complex either the Sonju Lake intrusion or the rocks assigned to the Beaver Bay Complex. In addition to the coarse-grained Sonju Lake and Beaver Bay rocks, the lava flows in this area are cut by numerous north- and northeast-trending hypabyssal diabase dikes and sills. Most consist of ophitic olivine diabase having rare plagioclase phenocrysts (Green, 1972). Sporatic occurrences of granophyre are associated with these hypabyssal rocks, and many of the larger hypabyssal intrusions contain large inclusions of anorthosite, as much as several kilometers across The plagioclase in these inclusions is compositionally similar to that found in the anorthositic and troctolitic rocks of the Duluth Complex (Table 2, figs 7 and 8), but it is coarse-grained (5-10 cm long crystals are common) and somewhat granulated. In addition, fresh samples of this anorthosite have a distinctive greenish hue compared to the blue-gray color of other anorthositic rocks in the Duluth Complex The host rocks commonly intrude the anorthosite, but the blocks are thought to have been rafted upward from some deep source (Grout and Schwartz, 1939). The origin of these inclusions is an important but as yet unresolved petrologic problem (Phinney, 1968).

DISCUSSION

The geologic relationship summarized above and portrayed in Figure 6 shows that in broad terms the Duluth Complex consists of a central cap of anorthositic series rocks underlain and surrounded by troctolitic-gabbroic rocks. Minor peridotite bodies are found at the base of the complex and irregular masses of felsic rocks sporadically intrude the anorthositic and troctolitic-gabbroic rocks, particularly along a north-northeast-trending linear zone in the upper part of the complex (fig. 6).

For the reasons cited above, we conclude that rocks of the anorthositic series are older than rocks of the troctolitic-gabbroic series. The age of the peridotite and the granophyre relative to that of the two major series is uncertain. Grout (1918f) concluded that all of these rocks at Duluth could have formed at about the same time by a unique combination of processes involving differentiation by crystal fractionation of a single magma.

Taylor (1964) concluded that the two major rock series at Duluth formed by different processes of differentiation. He did not relate the peridotite to either of the major series, but he implied that at least some of the rocks of the felsic series are a part of the differentiated units of the troctolitic-gabbroic series.

Phinney (1970) made a preliminary attempt at identifying a parental magma type for rocks of the Duluth Complex. He showed that the compositions of some of the more magnesium-rich flows of the North Shore Volcanic Group lie along a differentiation trend which could be produced by the removal of plagioclase from a high, Al-magma type (Table 1, analysis 15). Because he considered only Al_2O_3 and CaO in his analysis, it is not possible to relate uniquely the origin of either the anorthositic series or the troctolitic-gabbroic series to this magma.

There are several physical and chemical constraints which must be considered to establish the validity of general petrogenetic models, such as those proposed above. Specifically, in any attempt to relate a group of apparently cogenetic rocks to a common parental magma, one constraint is the chemical mass balance of all the major elements. In our mass balance calculations we are using a linear programming and least squares method (Wright and Doherty, 1970) which provides a convenient means of manipulating these large amounts of data. Three parameters are involved in mass calculations: (1) the original bulk chemical composition of the proposed parental magma; (2) the relative volumes of each of the rock units; and (3) the bulk chemical compositions of the different units. In layered intrusions the first parameter can be obtained from analyses of chilled margin material and the latter two estimated from structural, stratigraphic, and mineral compositional data. In many cases the bulk composition cannot be determined, but the latter two parameters can be estimated and balance calculations can be used to assign specific rock types to proposed parential magma compositions. The results must be evaluated in terms of crystallization sequences and relative mineral abundances determined from either experimental data, or from textures and relative volumes of different rock units used in the calculations.

The conspicuous absense of chilled margin material always has been considered a stumbling block in similar interpretive studies of the petrogenetic relationships in the Duluth Complex. However, extrusive and hypabyssal rocks, thought to be cogenetic with the Duluth Complex provide a suite of compositions which might reflect directly that of parental magmas or might define compositional trends resulting from the formation of layered rocks by crystal fractionation in magma chambers at depth.

Continuing the work of Phinney (1970) we are using mass balance calculations to determine probable parent magma types and to relate them to specific rock units in the Duluth Complex. Representative data from lava flows of the North Shore Volcanic Group (Green, 1972), Keweenawan hypabyssal rocks (Weiblen and Morey, 1972, Geul, 1970), and mineral compositional data (Table 2) from different rock units in the Duluth Complex are listed in Table 3. The preliminary studies have produced several surprising results. First, Mudrey (1973) has shown that the chilled margin of a sill on Pigeon Point has the composition of a high alumina-basalt similar in major element chemistry to that of the Skaergaard intrusion (Table 1, analysis 15). Mass balance calculations indicate that the troctolitic-gabbroic series rocks in the Duluth Complex could have been derived from a parental magma having a similar composition (Table 3, fig. 10). Mudrey also investigated the possibility that other Keweenawan hypabyssal rocks in northern Minnesota could be genetically related to this magma composition. He found that the Logan intrusions in the Gunflint Corridor (Weiblen and Morey, 1972) although lower in magnesium ($<$ 4%) could not be derived by any reasonable differentiation scheme from the high-alumina basalt magma. Mudrey discovered, however, that the composition of the Logan intrusions resembles the liquid composition (bulk composition minus phenocryst composition) of the magnetically reversed, lowermost flows of the North Shore Volcanic Group (Table 1, analysis 14). The bulk composition (including olivine and pyroxene phenocrysts) of these flows resembles the low-alumina basalt type "komatiite" recently recognized in lower Precambrian greenstone terranes. These observations led us to consider this lava composition as a possible parental magma for some units of the Duluth Complex. Subsequent analysis has shown that rock units similar in composition to the peridotite at Duluth, the anorthositic series rocks, and granophyre can be derived from this low-alumina magma composition in the approximate proportions of 65, 25, 10 weight percent (Table 3, fig. 10).

The above results are significant from a petrogenetic point of view in that they show that all the rock types in the Duluth Complex can be related to two parental magma compositions. The troctolitic-gabbroic units and the Skaergaard intrusion both exhibit well defined differentiation sequence (fig. 8) and both have a similar parental magma composition — that of high alumina basalt. The three heretofore unrelated rock units in the Duluth Complex (peridotite, anorthositic series rocks, and felsic series rocks) may now be genetically related to a common low-alumnia basalt magma. These results suggest that the bulk of the felsic series rocks formed from the low-alumnia magma type. Specific details regarding the differentiation process leading to the contrasting rock types which we have assigned to the low-alumnia magma remain an interesting but unresolved problem. In terms of the "normal" differentiation of basalt to felsite, Grout recognized a relative paucity of intermediate rocks at Duluth. He suggested that the felsic series rocks may have been formed by the separation of an immiscible silicate liquid during crystallization (Grout 1918f, p. 657). Subsequently, this process was discounted by most petrologists studying similar rocks, but the recent recognition of late-stage immiscibility in lunar basalts (Roeder and Weiblen, 1970, 1971; Rutherford and others, 1974) along with new evidence of immiscibility in terrestrial rocks (Philpotts, 1970) and the experimental confirmation of immiscibility in the Skaergaard magma (McBirney, 1975) implies that this process must be reconsidered in interpreting the genesis of the felsic series rocks in the Duluth Complex.

The two-magma petrogenetic model outlined above also is consistent with the observed Keweenawan stratigraphic relationships. That is, the lower, magnetically reversed lava flows of the North Shore Volcanic Group and the Logan intrusions appear to be genetically related to older anorthositic series in the Duluth Complex, whereas the younger, magnetically normal lava flows and other olivine diabase dikes and sills appear to be genetically related to the younger troctolitic-gabbroic series (fig 10).

STRUCTURE

The Keweenawan rocks in northeastern Minnesota are an integral part of the geologic structure generally referred to as the Midcontinent Gravity High (Thiel, 1956). The gravity high is due to a succession of mafic rocks which occur as a semicontinuous series of fault-bounded blocks forming a long, narrow belt that cuts across the pre-Keweenawan rocks of Michigan, Wisconsin, Minnesota, Iowa, Nebraska, and Kansas. The overall geometry of the structure and the distribution of rock types within it have many features analogous to those associated with known rift systems in other parts of the world (King and Zietz, 1971; Morey, 1972; Chase and Gilmer, 1973). Because faulting is the dominant geologic process in rift systems, it may be inferred that this process played a key role in the evolution of the Keweenawan terrane. Morey (1972) has shown that sedimentation and tectonism were contemporaneous processes and that the observed stratigraphic succession and distribution of sedimentary rocks in east-central and southeastern Minnesota were controlled largely by the faulting. Our review of the geologic relationships in the Duluth Complex, indicates that faulting must have been an important process in the evolution of the Keweenawan igneous rocks of northeastern Minnesota as well.

Unfortunately, to date very few faults have been documented by on-the-ground mapping in the Duluth Complex. Faults have been recognized where contacts between different rock types are displaced or where the rocks have been cataclasized. Because layering is not well developed in the anorthositic series and appears to be discontinuous along strike in the troctolitic-gabbroic series (Taylor, 1964, p. 15), unambiguous offset contacts are difficult to document, and cataclastic zones have not been looked for in detail. The presence of faults may be inferred indirectly from other data. For example, the distribution of rock types as inferred from geophysical anomalies has been used to define possible fault patterns, but this approach has only limited value in any detailed structural study where bedrock exposures are insufficient to adequately constrain the physical interpretations. Linear topographic lows may be bedrock controlled, and in the Duluth Complex, the coincidence of these lineaments with cataclastic zones or displaced contacts implies that some are fault controlled. A preliminary photogeologic-photogeomorphic interpretation utilizing topographic maps, high-level aerial photographs, and various kinds of ERTS imagery has shown the existence of numerous lineaments in the Duluth Complex. Studies are currently underway to document and describe the various kinds of lineaments present in the Duluth Complex and to evaluate them in terms of their tectonic significance Although these studies are incomplete we conclude that faulting may be much more extensive than can be implied from on-the-ground observations

We summarize below for each of the areas shown in Figure 1 the presently available on-the-ground and imagery-derived data used to prepare Figure 11, which is a generalized structural interpretation of the Duluth Complex. These data in conjunction with the structural history of other parts of the Midcontinent Gravity High and the structural history of other known rift systems will serve as a basis for evaluating the structural history of the Duluth Complex.

Duluth and Vicinity

No definitive evidence for faulting at Duluth was documented by Grout (1918) or Taylor (1964). However, several recent observations may be construed as evidence that faulting occurred. On the basis of displaced lava flow contacts, Kilburg (1972, p. 42, fig. 5) mapped a north-trending apparently near vertical, east side-up fault in the magnetically reversed lava flows of the North Shore Volcanic Group. In addition, Kilburg (1972, p. 11) described from near Ely's Peak, a north-trending brecciated zone between the lava flows and the troctolitic-gabbroic series of the Duluth Complex. No well defined, chilled margin material of the troctolitic-gabbroic series has been found in this zone; only coarse-grained anorthositic series rocks and peridotite are present, and these rocks could have been faulted to their present stratigraphic level. Lastly, most of the diabasic dikes in this area occupy north-trending fracture zones which more-or-less parallel the faults described above (Taylor, 1964, map).

Duluth to Hoyt Lakes Area

Two west-northwest-trending faults have been mapped in the Water Hen Creek intrusion south of Hoyt Lakes (J. W Mainwaring, in Bonnichsen, 1972, fig. v-51) on the basis of displaced contacts. The faults appear to delineate a west-northwest-trending horst about 700 meters wide. No other definitive evidence for faulting has been recognized in this drift-covered area of sparse exposures, but abundant north-northeast-trending lineaments are apparent on ERTS photographs. These lineaments may be geomorphic features formed during Pleistocene time, but their extensive development over rocks of the Duluth Complex implies that their orientation has been controlled by bedrock structures.

Hoyt Lakes—Kawishiwi Area

Phinney and Weiblen did not document any faults in their mapping of the Gabbro Lake quadrangle (Green and others, 1972). Bonnichsen (1970a), however, mapped several northeast- to north-northeast-trending faults that offset the basal contact of the complex in the Babbitt area. To judge from his map, displacements are small with the northwest side of each fault up thrown. Similarly, Sims (1974) noted several apparent offsets in the basal contact of the Duluth Complex between Babbitt and Gabbro Lake. These offsets are coincident with well developed north-northeast-trending topographic lineaments in the Duluth Complex. Consequently, he interpreted these lineaments to be the negative topographic expressions associated with faulted rock. Both the inferred faults and other lineaments have trends parallel to that of known faults in the immediately adjacent Lower Precambrian terrane suggesting that Lower Precambrian faults were reactivated during Keweenawan time The actual sense of motion along these faults is unknown but the geometry of the displaced contacts implies northwest side-up movement.

A preliminary analysis of high level 1:24,000 aerial photographs by Cooper (1975) indicates that north-northeast-trending lineaments are extensively developed in an area bounded on the north by the base of the complex and on the south by the Vermilion moraine (Wright, 1972, p. 521, fig. VII-2) a distance of about 16 kilometers. Additional mapping in the Gabbro Lake quadrangle by R. Beltrame, R. Cooper, and J. Dunlavey during the 1974 field season indicates that joints are well developed in proximity to many of the lineaments and that in some places rocks within the lineaments are cataclasized. Thus, it appears that many of the lineaments in this area are developed over fracture zones in the bedrock.

The contact between the troctolitic-gabbroic and anorthositic series in this area trends generally in an east-northeast direction (fig. 11), but it is broken by a number of north-northeast-trending extensions of troctolitic-gabbroic rocks into the anorthositic series rocks (fig. 11). These dike-like extensions more-or-less parallel many of the lineaments described above. As at Duluth, no evidence of a chilled margin has been found along these contacts. The general directions and possible locations of some faults which may be inferred from these observations are shown in Figure 11.

Boundary Waters Canoe Area

No faults have been mapped in the Boundary Waters Canoe Area (Phinney, 1972, p. 335, V-26). Here again irregular offsets of the basal contact along a northerly direction, dike-like extensions of troctolitic-gabbroic series rocks into anorthositic series rocks, and the general alignment of isolated exposures of felsic series rocks along north-northeast-trending zones are interpreted as indications of faults whose directions are consistent with those recognized and postulated in the Hoyt Lakes-Kawishiwi area.

Gunflint Corridor

Numerous faults displacing rocks of Keweenawan age have been recognized in the Gunflint Corridor. Morey (1965), Morey and others (1969) and Mathez (1971) have mapped a number north-northwest-trending faults in the South Lake, Long Island Lake, and Hungry Jack Lake quadrangles. All have small amounts of vertical displacement in which the southwest sides are up thrown. Morey (1965), Morey and others (1969) and Mathez (1971) also recognized several small magnitude, west-northwest-trending, south side-up faults. The west-northwest-trending faults displace only the Logan intrusions and older rocks; and their age, relative to that of the Duluth Complex, is unknown. However, the north-northwest-trending faults appear to be both younger and older than the Duluth Complex. The faults mapped by Mathez (1971) appear to offset rocks of Nathan's layered series, whereas those that project toward the Tuscarora intrusion in the Long Island Lake quadrangle do not displace the basal contact.

Nathan (1969) recognized one north-northwest-trending fault on the basis of displace contacts in his layered series. The relative magnitudes of vertical and horizontal displacement are unknown, but the vertical displacement is east side-up. Nathan also discussed the possible presence of other more-or-less parallel faults, but he was unable to document their presence with certainty.

The rocks of Nathan's layered series are truncated to the west by the somewhat younger Tuscarora intrusion, and the two units are apparently juxtaposed along a north-trending topographic lineament (fig. 9). Again, however, there is no evidence of a chilled margin in the troctolitic-gabbroic rocks.

Lastly, isolated masses of felsic series rocks have a strikingly linear distribution along a zone which extends northward from Lake Superior to the vicinity of the International boundary near Gunflint Lake, a distance of over 100 kilometers. The coincidence of felsic rocks within cataclatized zones in other parts of the Duluth Complex implies that the linear distribution of these felsic rocks reflects a fundamental structural discontinuity.

Finland-Beaver Bay Area

Stevenson (1974) delineated several north-northeast-trending, left-lateral or southeast side-up faults in the troctolitic-gabbroic Sonju Lake intrusion north of Finland. These faults more-or-less coincide with the east edge of the Beaver Bay Complex and associated differentiated rocks of the troctolitic-gabbroic series and are parallel to the direction defined by exposures of felsic series rocks in the Gunflint Corridor. The Beaver Bay Complex and associated troctolitic-gabbroic rocks occur as dike-like extensions of plutonic and hypabyssal rocks into lava flows of the North Shore Volcanic Group. These dike-like bodies are parallel to similar dike-like bodies previously described in the Hoyt Lakes Kawishiwi area.

The rocks and faults of the Finland-Beaver Bay area also are part of a major structural discontinuity that separates the Keweenawan rocks into two terranes each having distinctly different geological, geophysical, and ERTS imagery attributes.

Discussion

The structural observations on the Duluth Complex summarized above and compiled in Figure 11 are typified by a number of general characteristics: (1) The fault trends are inferred from lineaments and displaced contacts, but they are also coincident with cataclastic zones and linear occurrences of granophyre. (2) The faults have three general trends; north-northeast, north-northwest and west-northwest. (3) In the Hoyt Lakes- Kawishiwi area the fault directions recognized are sub-parallel to faults formed during early Precambrian time. (4) In the Gunflint Corridor there is a record of successive periods of faulting within the complex during Keweenawan time. (5) The spatial and stratigraphic distribution of various rock units within the complex is probably fault controlled.

These structural features were unknown to early workers who because of the general dip of 15°-25° to the southeast considered the Keweenawan rocks of northern Minnesota to be a simple sheet-like mass which defined the north limb of the so-called "Lake Superior syncline" (for summary, see Craddock, 1972 p. 289). White (1966) suggested major modifications to this simple structural interpretation He recognized three distinct stages in the tectonic evolution of the

Keweenawan rocks in the western Lake Superior region. These include: (1) The accumulation during Middle Keweenawan time of a thick series of lava flows and mafic intrusions in two basins separated by a north-northeast-trending high extending from near the Bayfield peninsula on the south shore of Lake Superior toward Beaver Bay in Minnesota; (2) The development during Late Keweenawan time of the east-northeast-trending "Lake Superior syncline;" and (3) The development of late faults such as the Keweenawan fault in Michigan, and the Douglas and Lake Owens faults in Wisconsin. White based his interpretation primarily on gravity and magnetic data from the western part of Lake Superior supplemented by geologic data pertaining principally to Keweenawan lava flows. Wieblen and others (1972a) integrated parts of White's model into a general structural model for northeastern Minnesota. They suggested that the axis of the Middle Keweenawan positive area extended into Minnesota and served as a locus for tectonism which produced void spaces into which the Logan intrusions were passively emplaced. Subsequently, Wieblen and others (1972b) expanded that interpretation and postulated that the early period of arching north-northeast was followed by a second period of faulting parallel to the arch and to the axis of the "Lake Superior syncline." Weiblen and others (1972) later correlated distinct magma types with these two tectonic stages. They postulated that a parent magma for the anorthositic series and associated rocks was related to the early stage of tectonism, whereas the parent magma of the troctolitic-gabbroic series rocks was related to the second stage.

All of the above interpretations serve to establish a rational sequence of events during Keweenawan time, but they do not provide a mechanistic explanation for the emplacement of the Duluth Complex and associated rocks. In this report we propose to use current concepts regarding oceanic rifting processes (Rea, 1975) to evaluate the significance of the structural characteristics enumerated above. The analysis that follows must be considered exploratory because analogies between continental and oceanic rifting processes may not be entirely appropriate.

Some of the salient structural elements associated with oceanic rift systems are illustrated in Figure 12. These include: (1) vertical faults at the surface which decrease in dip toward the spreading axis at depth, (2) fault-bounded axial blocks having a keystone geometry, (3) faults having either normal or reverse motion depending on their location relative to that of the spreading center. We suggest however that rifting in a continental environment may be more complicated than that shown in Figure 12 because of inherent structural inhomogenities in axial blocks composed of continental materials, variable density contrasts between foundered continental blocks and rising magmas in the rift system, and asymmetric spreading in which only one side of the rift system actively moves

Our petrogenetic analysis has led to the conclusion that the Duluth Complex may be viewed as a series of older rock units (peridotite, anorthositic series rocks, and granophyre) derived from a low-Al magma and a younger troctolitic-gabbroic series derived from a high-Al magma. The peridotite occurs as part of the basement intruded by the high-Al magma and the anorthositic series rocks and granophyre occur as inclusions and roof rocks for the troctolitic-gabbroic series rocks. The fact that the different rock units of the complex can be assigned to mantle-derived magma types suggests that assimilation of crustal material probably did not play an important role in their emplacement. Separation of older crustal rocks by rifting (fig. 12) provides a mechanism for developing void space for the magma chambers. The contrasting rock types in the different units of each magma series requires magma chambers isolated from their magma sources so that crystal fractionation could occur on a scale large enough to separate the observed volumes of plagioclase of relatively uniform composition (fig. 8) from peridotite in the low-Al magma series rocks and to develop the differentiated unit found in the troctolitic-gabbroic rocks. Foundering of axial blocks provides a convenient mechanism for separating magma from its source to develop the cooling conditions required by the observed fractionation (fig. 12). The rate of spreading, the rate of magma generation, relative super-heat and viscosity of a magma, density contrasts between magmas and axial blocks, structural and density inhomogeneties in the axial blocks will all affect the shape and size of magma chambers and the cooling history.

The extensive fractionation required to produce the different units in the low-Al magma series rocks suggests foundering of axial blocks followed by relatively long periods of tectonic quiescence. On the other hand, the multiple fractionation and the discontinuous nature of the resulting layering in the troctolitic-gabbroic series rocks suggests more episodic tectonism. A two-stage model of magmatism and tectonism is suggested, finally, because the rocks of the older low-Al magma series are involved in the emplacement of the younger high-Al series rocks.

To illustrate these concepts, we have prepared a cross section extending from the Kawishiwi River to Lake Superior north of Beaver Bay (fig. 13). The shape and relative motions of the postulated fault are presumed to coincide with the general relationships illustrated in Figure 12. We have assumed that a total separation of 24 kilometers occurred along this section. This is the amount of separation implied by Chase and Gilmer (1973) in their rifting model. A sequence of cross sections illustrates the development of void spaces (fig. 13a-d), foundering of axial blocks (fig. 13b-d), and the involvement of the low-Al magma series rocks in the emplacement of the high Al-magma series rocks (fig. 13d). This succession of events followed by erosion leads to the observed geologic relationships illustrated in Figure 13e The geologic relationships at depth postulated in this cross section are consistent with a qualitative interpretation of available geophysical data to the extent that gravity maxima occur over the Bald Eagle and Sonju Lake intrusions (Ikola, 1970).

In detail, we suggest the following sequence of events leading to geologic relationships observed along the line of section. (1) Initial separation along a north-northeast-trending direction resulted in the emplacement of hypabyssal rocks and magnetically reversed lava flows of the North Shore Volcanic Group. (2) As separation continued, a volcanic edifice and associated magma chambers formed over a width of approximately 25 kilometers Approximately 8 kilometers of actual separation and a foundered axial block 18 kilometers in width appear to be adequate to produce a magma chamber of this size. We infer that after the low-Al magma was emplaced and during a period of relative tectonic quiescence, peridotite segregated from the anorthositic rocks and late granophyre at depth beneath a roof of magnetically reversed lava flows and hypabyssal sills. Although we illustrate a structurally simple axial block in Figure 13c, extensive fragmentation of this block may have occurred along vertical faults giving rise to the same amount of anorthositic series rocks by a more complex process. The auto-brecciated nature of the anorthositic rocks may have developed in part by fragmentation at this stage. (3) After the low-Al magma segregated into the various differentiates of the anorthositic series rocks as crystal mushes, but probably before complete solidification occurred, renewed separation disrupted the initial volcanic edifice and created new magma chambers which, at this stage, were filled by a high-Al magma. Again, the foundering of axial blocks produced isolated magma chambers in which troctolitic and gabbroic rocks formed. Both the Bald Eagle and Sonju Lake intrusions occur along the edges of the axial blocks and we envision them to be major feeder systems for the troctolitic-gabbroic series rocks. We explain the asymmetry of the Bald Eagle intrusion with steep contacts on the east and shallow and disrupted contacts on the west by tilting of an axial block as shown in Figure 13d. That fragmentation of the older volcanic edifice occurred at this stage is indicated by the presence of kilometer-sized inclusions of anorthositic series rocks in the Kawishiwi intrusion. Tilting of an axial block in the vicinity of the Kawishiwi River during this stage could have resulted in the penecontemporaneous erosion of older magnetically reversed flows; consequently, their preservation in this area would be restricted to downthrown blocks which now occur as hornfels inclusions in the troctolitic-gabbroic series rocks. (4) Although we infer that faulting occurred dominantly during emplacement of the igneous rocks, there is no reason to assume that motion along these faults ceased entirely with the cessation of magmatic activity in Middle Keweenawan time. Many of the faults associated with the Midcontinent Gravity High in southeastern Minnesota were periodically active during Cambro-Ordovician time (Morey and Rensink, 1969), and perhaps during Pleistocene time (Hogberg, 1975). Erosion during Late Keweenawan to Pleistocene time removed much of the volcanic edifice and lead to the exposure of plutonic, hypabyssal and extrusive rocks shown in Figure 13e.

IMPLICATIONS OF THE MODEL

The general petrogenetic-tectonic model outlined above and summarized in Figure 14 has many geologic implications. In this report however, we will touch on only those relevant to the exploration and development of the copper-nickel mineralization. Briefly, the model suggests several new insights into the general problem of the distribution of sulfide-bearing rocks in the complex:

(1) Surface mapping and diamond drilling indicate that the copper-nickel mineralization is restricted dominantly to basal units of the troctolitic-gabbroic series (Bonnichsen, 1972; Wager and others, 1969). This suggests that areas underlain by anorthositic series rocks, where reliably mapped, can be excluded from consideration as potential sites for copper-nickel mineralization. However, our model suggests that areas of sparse exposures in the central part of the complex presently mapped as anorthositic gabbro could conceivably be underlain by troctolitic-gabbroic series rocks with anorthositic inclusions (fig. 13d, e and fig. 14). Consequently, basal rocks like those present in the Kawishiwi intrusion might be repeated in other areas. Geophysical methods would have to be used to evaluate this implication.

(2) If the introduction of sulfur into the troctolitic-gabbroic series magma played a role in the origin of the copper-nickel deposits as suggested by Weiblen and Perry (in prep.), the postulated faults most likely served as channel ways along which a sulfur-bearing gas phase migrated from the country rocks or inclusions into the adjacent magma. Further, if lineaments and cataclastic zones reflect these faults at depth, they are likely targets for exploration.

(3) Our petrogenetic and tectonic model places no constraints on the size of any given rock unit, either with regard to its persistence along strike or extension at depth. One might view the entire Kawishiwi-Hoyt Lakes area as being underlain by a single intrusion of troctolitic-gabbroic series rocks fed through the Bald Eagle intrusion. Conversely, rocks fed through the Bald Eagle intrusion might be localized essentially to the confines of the Gabbro Lake quadrangle. This uncertainty results from the fact that the north-northeast-trending faults shown in Figure 11 must be bounded along transform or strike-slip faults trending in a general easterly direction. The north-northwest-trending faults cutting the Water-Hen Creek intrusion in the Duluth-Hoyt Lakes area may be examples of such faults, but at present there are no constraints on the distribution of similar faults. A better understanding of the distribution of rocks in the Hoyt Lakes-Kawishiwi area might be greatly facilitated by the careful search for additional faults of this type.

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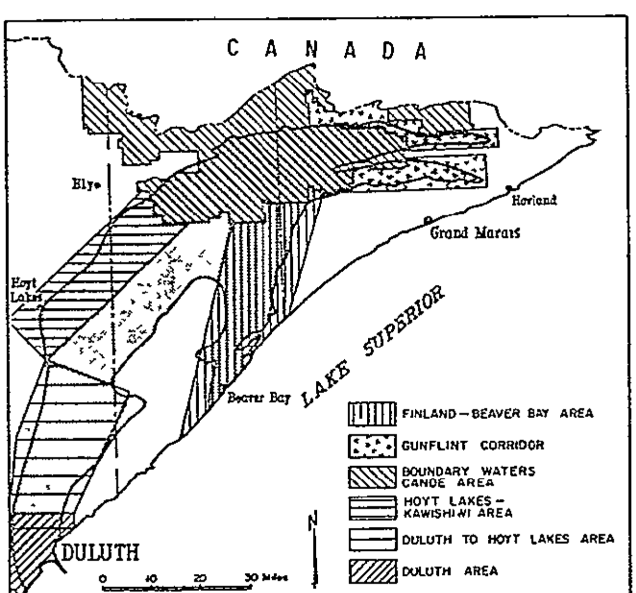

FIG. 1

Figure 1. Location map of the Duluth Complex

Boundaries of the complex are from Sims (1970). For purposes of presentation and discussion of geology in this report, the complex has been divided into the six geographic areas shown. These subdivisions are not entirely arbitrary because the access, nature of the exposures, and the geology are somewhat distinct in each. Moreover, the subdivisions more-or-less delineate terranes mapped by different individuals at different times.

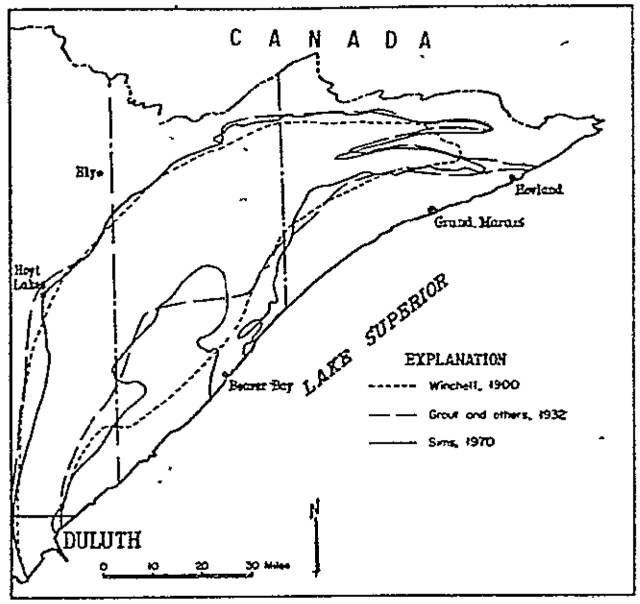

Figure 2. Changes in the generalized contacts of the Duluth Complex from 1900 to 1970.

Superposition of the generalized contacts of the Duluth Complex as drawn on three successive state maps shows that the lower contact has not been revised significantly, whereas each new interpretation of available data on the upper contact has resulted in drastic changes. See text for further discussion.

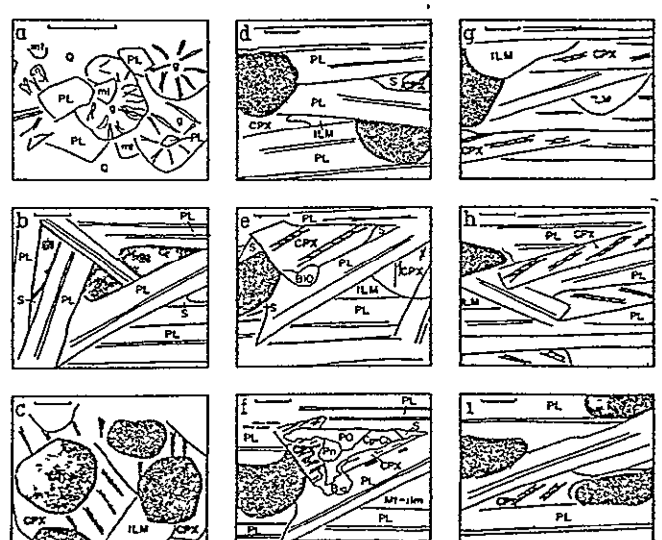

Figure 3. Diagrammatic sketches of typical textures in rocks of the Duluth Complex.

The bar scale in each diagram is approximately 2 mm in length. Q, quartz; Pl, plagioclase; Mt, magnetite; g, myrmekitic intergrowths of quartz and feldspar; Ol, olivine; ILM, ilmenite; CPX, clinopyroxene; s, symplectite; BIO, biotite; PO, pyrhotite; Pr, pentlandite; and Cp + Cb, chalcopyrite-bornite intergrowths. a, Felsic series granophyre. Radiating intergrowths of quartz and feldspar (albite and/or potassium feldspar, right side of figure) produce a myrmekitic texture in some granophyre (Taylor, 1964, p. 39). This texture commonly is disrupted by granular intergrowths of quartz and feldspar shown on the left side of the figure (Taylor, 1964, p. 38). Combination of these two textures define a granophyric texture. b, Anorthositic series rocks. Tabular plagioclase grains form a framework within which olivine, pyroxene, and/or iron-titanium oxides occur as interstitial grains. In some samples individual interstitial grains may be randomly oriented or optically continuous from one void to the next forming oikocrysts and a poikilitic texture (Weiblen, 1965, p. 77, fig. b; Phinney, 1972, p. 342, fig. V-28D). Further textural complexities may include hypersthene overgrowths on olivine (Phinney, 1972, p. 342, fig. V-28C). symplectic intergrowths of hypersthene and plagioclase (s) (Phinney, 1972, p. 344, fig. V-30C) or late interstitial intergrowths of iron-titanium oxides with biotite and/or granophyre (Phinney, 1972, p. 344, fig. V-30B and D). c, Peridotite. Euhedral to subhedral olivine is enclosed within oikocrysts of clinopyroxene. Ilmenite fills voids between clinopyroxene grains. d-f, Troctolitic-gabbroic series having textures formed by processes in which gravity settling predominated over flow. d, Layered troctolite. Euhedral to subhedral olivine is intergrown with tabular subparallel grains of plagioclase (Phinney, 1972, p. 329, fig. V-29A). Variations in olivine content gives the rock a layered fabric. Clinopyroxene, ilmenite-biotite intergrowths, and plagioclase-hyperthese symplectite fill spaces between plagioclase and olivine as described for textural type b. This textural type occurs in the upper parts of troctolitic-gabbroic intrusions. e, Augite-troctolite. Euhedral to subhedral olivine is intergrown with randomly oriented, tabular grains of plagioclase. Clinopyroxene, ilmenite, and biotite have a similar textural occurrence to that in d above, but are more abundant. This textural type occurs in border zones of troctolitic-gabbroic intrusions (Phinney, 1969, p. 15). f, Mineralized augite-troctolite. This textural type is similar to e above except that copper-nickel sulfide minerals are included in and intergrown with the interstitial silicate minerals. Sulfides also occur as inclusions in the borders of plagioclase grains. This textural type occurs at the base of some troctolitic-gabbroic intrusions (Bonnichsen, 1972, p. 388-393). g-i, Troctolitic-gabbroic rocks having textures formed by processes in which flow predominated over gravity settling. These textural types occur in stratigraphic successions in which the crystallization sequence is defined by the successive appearance of subhedral to euhedral minerals. They also are characterized by a paucity of late interstitial material compared with textural types and d through f above (Weiblen, 1965, p. 82-97, and 126; Beitsch, in prep). g, Oxide gabbro. Magnetite-ilmenite, clinopyroxene, and plagioclase occur as subhedral to euhedral grains. Tabular pyroxene and plagioclase commonly define a foliated or lineated fabric. Apatite may occur as an important interstitial or subhedral to euhedral constituent in this textural type (Weiblen, 1965, p. 96, fig. C). H, Gabbro. Olivine-gabbro similar to textural type g above except that the magnetite-ilmenite occurs as interstitial grains (Weiblen, 1965, p. 92-95). i, Troctolite, similar to textural type g and h above except that clinopyroxene is interstitial; magnetite-ilmenite is a minor interstitial phase. This textural type is commonly modified by serpentination of the olivine which results in irregular fractures in olivine and radiatings fractures in the plagioclase (Weiblen, 1965, p. 82-87). Textural types c, h, and g define the crystallization sequence: olivine, plagioclase, clinopyroxene, magnetite-ilmenite, apatite in troctolitic-gabbroic series intrusions.

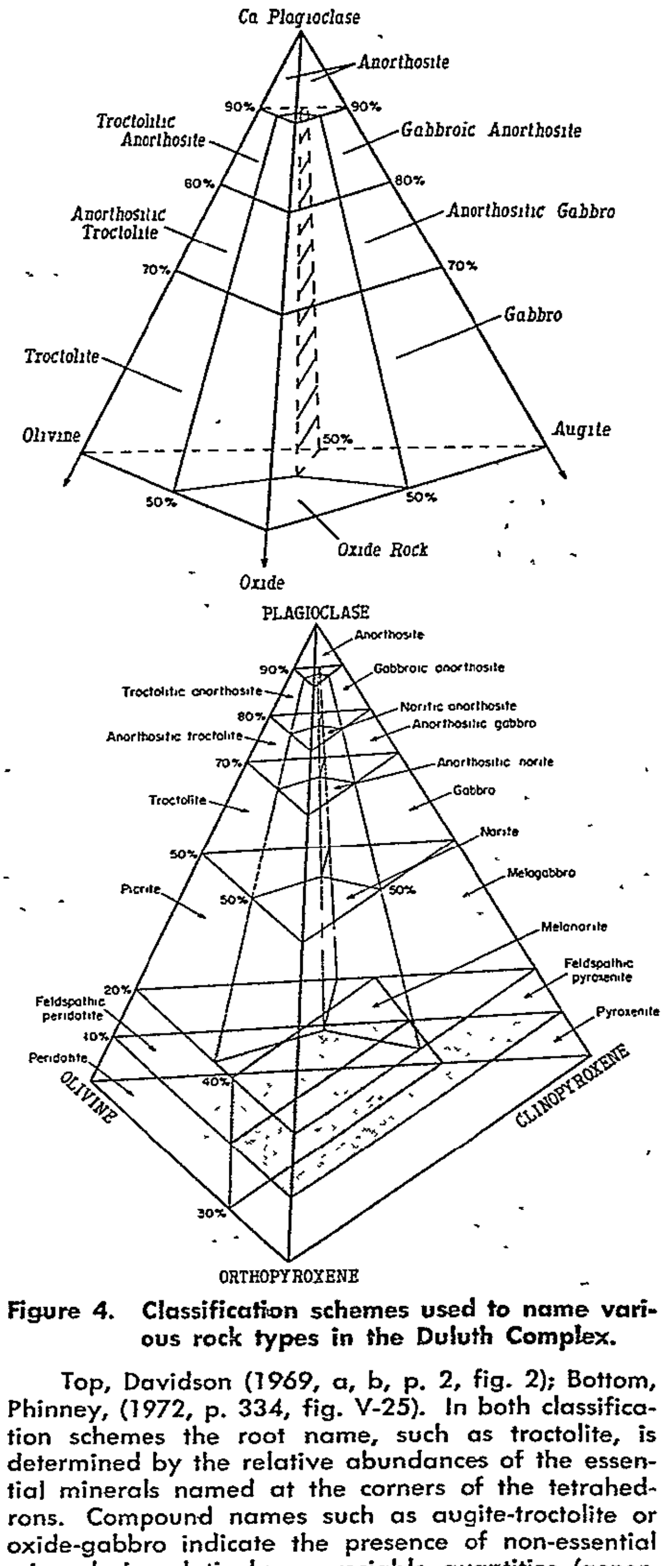

Figure 4. Classification schemes used to name various rock types in the Duluth Complex.

Top, Davidson (1969, a, b, p. 2, fig. 2); Bottom, Phinney, (1972, p. 334, fig. V-25). In both classification schemes the root name, such as troctolite, is determined by the relative abundances of the essential minerals named at the corners of the tetrahedrons. Compound names such as augite-troctolite or oxide-gabbro indicate the presence of non-essential minerals in relatively appreciable quantities (generally greater than 10%). Textural terms such as "poikilitic" also have been used as modifiers of the root name (Phinney, 1969).

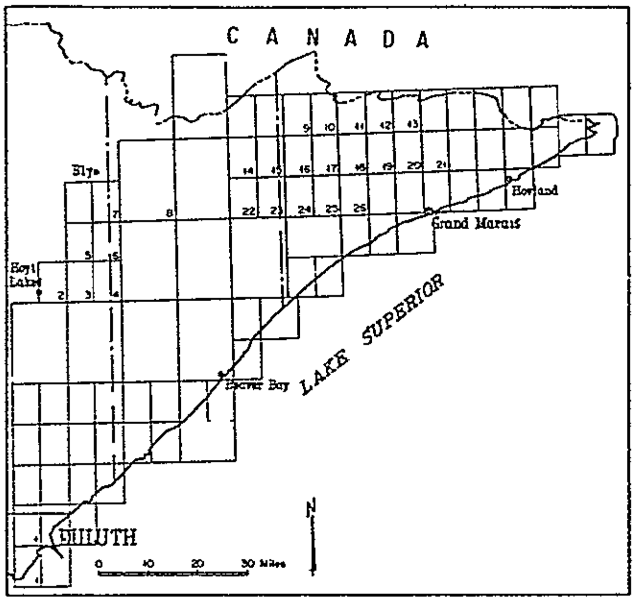

Figure 5. Index map showing quadrangles where the Duluth Complex has been mapped in some detail.

(1) Duluth and vicinity (Taylor, 1963); (2) Allen quadrangle (Bonnichsen, 1970, open-file map); (3) Babbitt S W. quadrangle (Bonnichsen, 1970, open-file map); (4) Babbitt S.E. quadrangle (Bonnichsen, 1970, open-file map); (5) Babbitt quadrangle (Bonnichsen, 1970, open-file map); (6) Babbitt N.E. quadrangle (Bonnichsen, 1970, open-file map); (7) Kangas Bay quadrangle (Bonnichsen, 1970, open-file map); (8) Gabbro Lake quadrangle (Green and others, 1966); (9) Gillis Lake quadrangle (Beitch, in prep); (10) Long Island Lake quadrangle (Morey and others, 1969, open-file map); (11) Gunflint Lake quadrangle (Nathan, 1969); (12) South Lake quadrangle (Nathan, 1969); (13) Hungry Jack Lake quadrangle (Nathan, 1969); (14) Crocodile Lake quadrangle (Babcock, 1959); (15) Alice Lake quadrangle (Davidson, in press); (16) Lake Polly quadrangle (Davidson, in press); (17) Kelso Mountain quadrangle (Davidson, in press); (18) Cherokee Lake quadrangle (Davidson, in press); (19) Brule Lake quadrangle (Davidson, in press); (20) Eagle Mountain quadrangle (Davidson, in press); (21) Lima Mountain quadrangle (Davidson, in press); (22) Pine Mountain quadrangle (Davidson, in press); (23) Perent Lake quadrangle (Davidson, 1969b); (24) Kawishiwi Lake quadrangle (Davidson, 1969a); (25) Beth Lake quadrangle (Davidson, in press); (26) Sawbill Camp quadrangle (Davidson, in press); (27) Tarit Lake quadrangle (Davidson, in press). In addition, an outcrop of the southern part of the Duluth Complex from Duluth to Hoyt Lakes has been published by Bonnichsen (1970c).

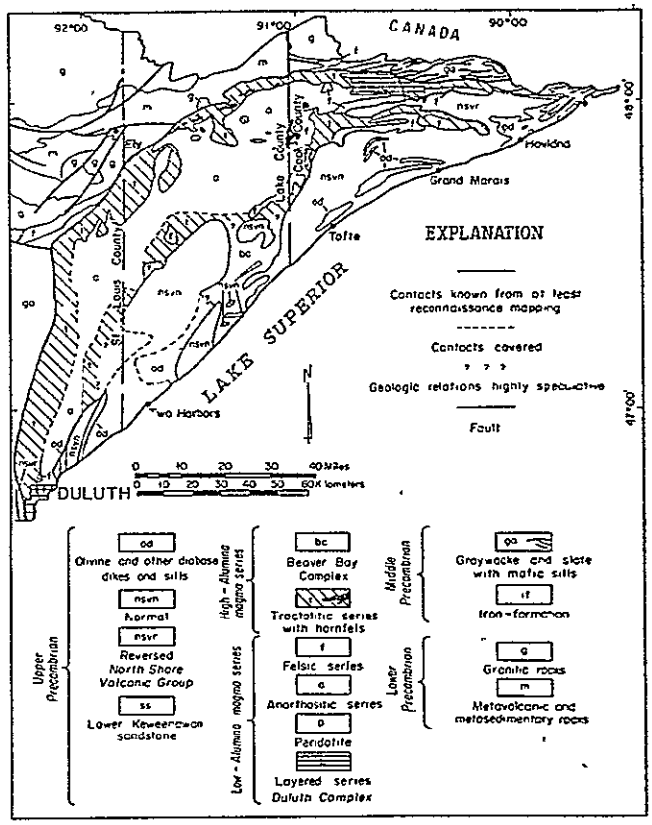

Figure 6. Generalized bedrock geologic map of the Duluth Complex and associated rocks.

This map has been compiled from quadrangle-scale maps referenced in Figure 5 and from sources discussed in the text. Note that only major rock units are shown. See references cited in the bibliography and Chapter V in Geology of Minnesota: A centennial volume (Sims and Morey, 1972) for specific details.

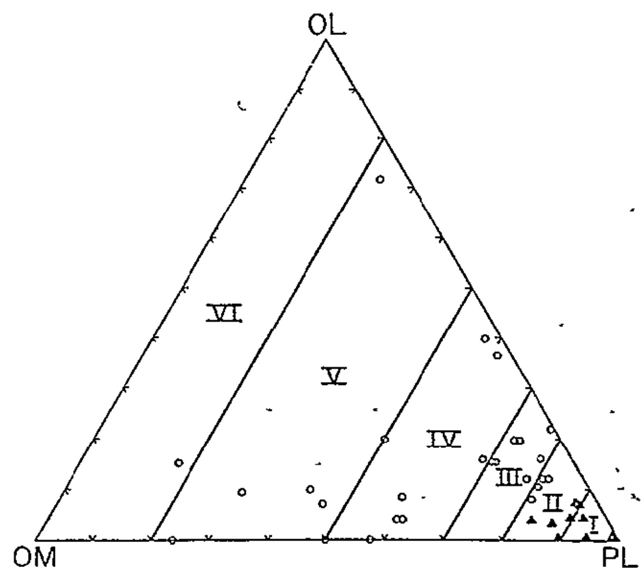

Figure 7. Plot of mineral abundance data for anorthositic and troctolitic-gabbroic series rocks from the Duluth Complex.

Modal data on plagioclase (P1), olivine (O1), and other mafic minerals (Om), including clinopyroxene, orthopyroxene, and magnetite-ilmenite have been normalized to 100% on this diagram. The fields shown define a possible rock nomenclature. Fields II through V may be subdivided by a line perpendicular to the O1-Om side of the triangle resulting in fields for olivine-rich rocks (troctolites) on the O1-P1 side (a) and pyroxene-oxide-rich rocks (gabbro and oxide gabbro) on the Om-P1 side (b). I, Anorthosite; IIa, Troctolitic anorthosite; IIb, Gabbroic anorthosite; IIIa, Anorthositic troctolite; IIIb, Anorthositic gabbro; IVa, Troctolite; IVb, Gabbro; Va, Picrite; Vb, Melagabbro; and VI, Peridotite. The last field may be subdivided into feldspathic peridotite and peridotite at a level of 10% plagioclase content and into pyroxenite-peridotite at a level of 30% of pyroxene content. The data are from Taylor, 1964, p. 11 and 16; Phinney, 1972, p. 336 and 337; and Davidson, 1972, p. 356. Individual data points represent averages of many samples in most cases (see refs.). Thus, the spread of mineral composition is greater than shown. The distribution of compositions plotted, however, illustrate the general observation that on the average the anorthositic series rocks (closed triangles contain more plagioclase than the troctolitic-gabbroic series rocks (open circles). The plot illustrates the problem of rock nomenclature for the Complex. For example, with the nomenclature used for this plot, four samples from the troctolitic-gabbroic series plot as troctolitic-gabbroic anorthosites and seven others as anorthositic troctolites. The latter two terms have been used extensively in the part to refer to rocks of the anorthositic series.

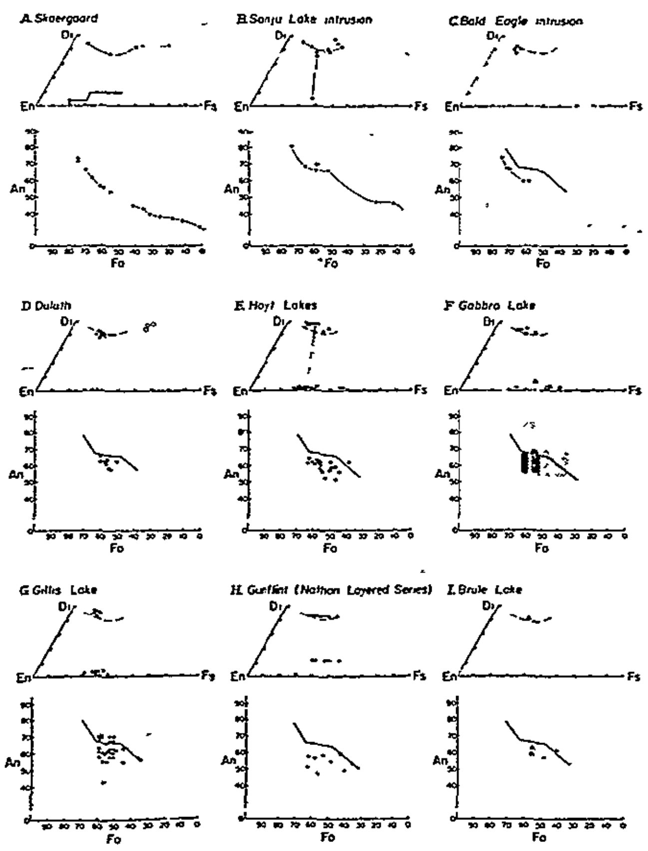

Figure 8. Pyroxene, plagioclase and olivine compositional data from the Skaergaard intrusion and various units in the Duluth Complex.

Closed circles refer to data from troctolitic-gabbroic series rocks; open circles refer to pyroxene data from differentiated rocks of the felsic series at Duluth; open triangles refer to data from anorthositic series rocks; pluses refer to data from rocks from the Gunflint Corridor studied by Nathan. Di-diopside, En-enstatite, Fs-wollastonite, An-anorthosite, and Fo-forestite. Dashed line in the pyroxene quadilateral and solid line in the plagioclase-olivine diagram in Figures C-I indicate the trend of the Sonju Lake intrusion (fig. B). Dark and light shaded areas indicate units Ago and Agu respectively mapped in the Gabbro Lake quadrangle in the anorthositic series by Phinney (1969). The diagrams illustrate the restricted differentiation trend recognized in the Duluth Complex compared to the Skaergaard intrusion (A) with the exception of the Sonju Lake intrusion (B). Trends on the An-Fo diagram reflect the unique fractionation and equilibration styles in different intrusions (Weiblen and others, 1975). The available data on the anorthositic series suggests equilibration of large volumes of rock to a common temperature without significant successive fractionation whereas the data on the troctolitic-gabbroic rocks approaches (B) the extensive fractionation observed in the Skaergaard intrusion (A). Data from: A, Wager and Brown, 1967, p. 34 & 39; B, Stevenson, 1974, p. 105 & 107; C, selected data from Weiblen, 1965, p. 123, 134-148; D, Taylor, 1964, p. 17 & 27; E, Hardyman, 1969, p. 34, 41-42; F, Phinney, 1969, p. 9; G, Beitsch, in prep; H, selected data from Nathan, 1969 and Phinney, 1972, p. 349; I, Davidson, 1972, p. 356. Average values have been plotted for ranges of compositions. Except for the detailed analyses by Hardyman (1969) and Stevenson (1974) the distribution of data in these plots provide only a qualitative indication of compositional trends.

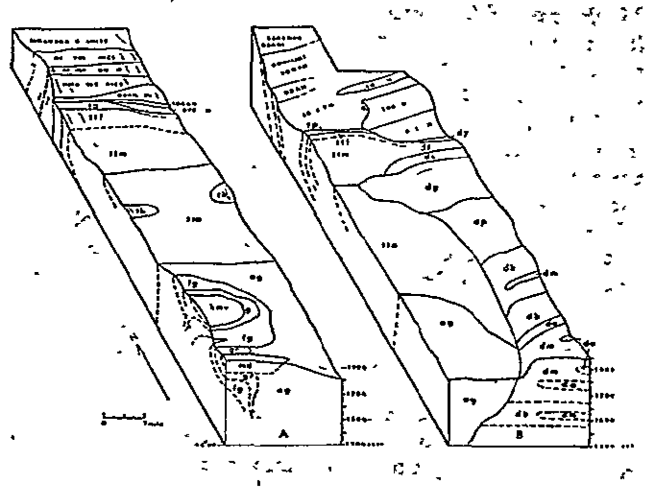

Figure 9. Structural block diagrams showing the inferred geologic relationships of rock units in part of the Gunflint Corridor.

(A) Long Island Lake quadrangle (Morey and others, 1969); (B) Gunflint Lake quadrangle (Nathan, 1969). 1d, Logan intrusions; tp, fine- to medium-grained augite troctolite; ttf, fine-grained troctolite; tm, medium-grained troctolite; tta, interlayered poikilitic augite gabbro and troctolite; th, hornfels; ag, anorthositic gabbro; fg, ferrogranodiorite; gr, granophyre; md, metadiabase; kmv, Keweenawan metavolcanic rocks; da-dm, various units of Nathan's layered series. See text and references cited therein for discussion. Note that a north-trending topographic lineament separates Nathan's layered series and somewhat younger troctolitic-gabbroic rocks. This lineament is parallel to the inferred, general northeast fault trends shown in Figure 11.

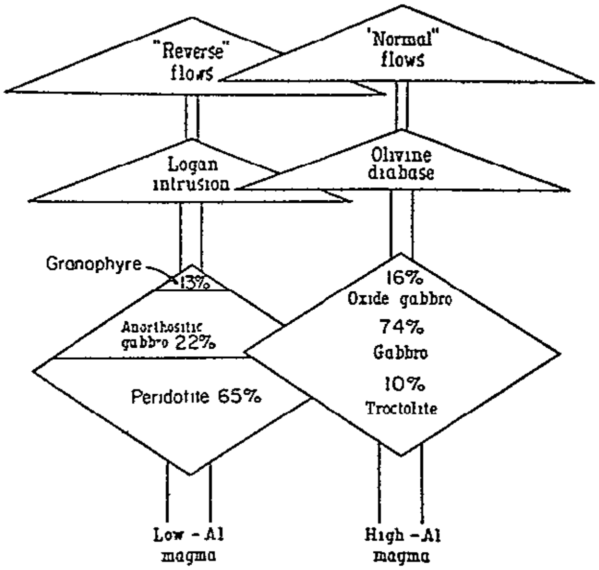

Figure 10. Schematic diagram summarizing results of petrologic mixing calculations discussed in text.

These calculations (Table 3) show that all the rock types in the Duluth Complex can be related to two parental magma types, an older low-Al magma and a somewhat younger high-Al magma. The calculations also are consistent with observed Keweenawan stratigraphic relationships in that the lower lava flows of the North Shore Volcanic Group and the Logan intrusions are related to the anorthositic series rocks, whereas the upper lava flows and other olivine diabase dikes and sills are related to the troctolitic-gabbroic series rocks. See Figures 13 and 14.

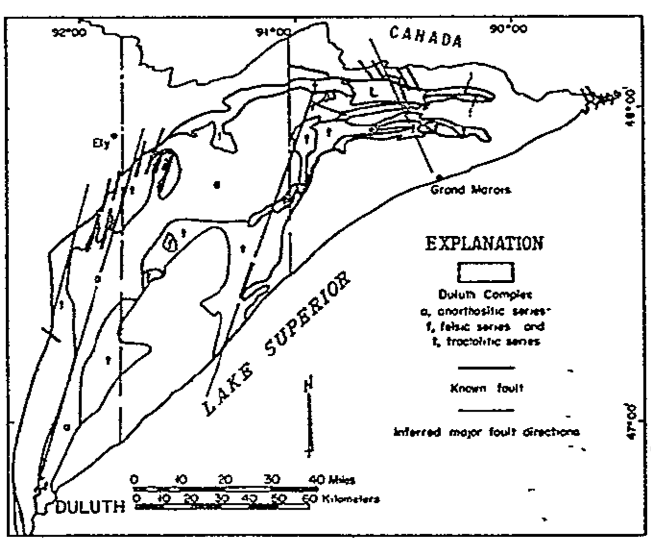

Figure 11. Generalized structure map of the Duluth Complex showing known faults and inferred major fault directions.

Geology generalized from Figure 6. The Gunflint Corridor and the Brule River Prong are dominated by northwest-trending faults and the rest of the Complex to the west and southwest by northeast trending faults. See text for further discussion and references to data used to compile this map.

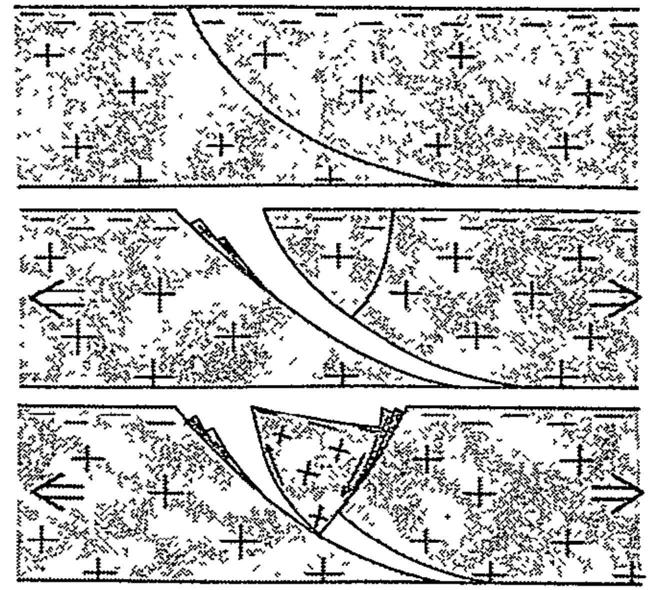

Figure 12. Diagrammatic sections showing some of the salient structural elements associated with rift systems.

Wedge-shaped void spaces develop by lateral separation along faults which are vertical near the surface and flatten at depth. Such voids may be filled with magma from below or sediment from above. Foundering of a hanging wall or keystone block will depend on structural inhomogenities in the block, density contrasts between block and margin, and rate of separation. Foundering of such blocks provides a method for separating magma from its source. The keystone block is bounded by curved faults having either normal or reverse motions depending on their locations relative to that of the spreading center. See Rea, 1975 and text for further discussion.

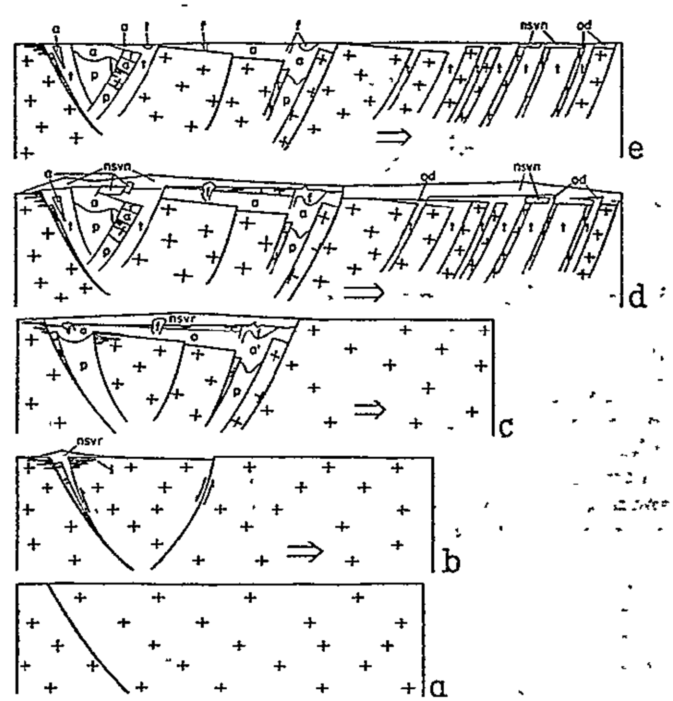

Figure 13. Generalized structure sections illustrating the inferred relationships between tectonism and magmatism in the Duluth Complex and associated rocks and a series of stages in the evolution of the Keweenawan terrane, northwest-southeast.

The sections are drawn along a northwest-southeast line 13 km east of Ely (left) and 20 km northwest of Beaver Bay (right) (fig. 1). Section e crosses the Bald Eagle intrusion (Weiblen, 1965) at symbol (t) and the Sonju Lake intrusion (Stevenson, 1974) just to the left of the symbol (nsvn). a, incipient faulting. b, emplacement of hypabyssal sills and dikes of Logan composition, and extrusion of magnetically reversed lava flows of the North Shore Volcanic Group (nsvr). c, separation with emplacement of low-Al magma in void spaces where it segregates into anorthositic series rocks (a), peridotite (p), and felsic series rocks (f). d, continued separation with emplacement of high-Al magma in void spaces where it differentiates into various rock units of the troctolitic-gabbroic series (t). Hypabyssal bodies of olivine diabase (od) also are emplaced during this stage are magnetically normal lava flows of North Shore Volcanic Group (nsvn). e, post-erosion and present subcrop distribution of rock types along the section. See text for additional discussion.

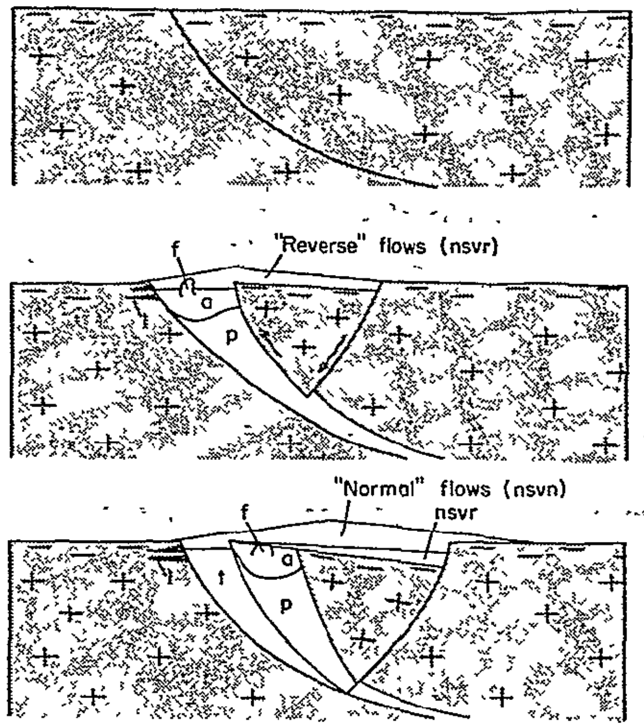

Figure 14. Diagrammatic sections summarizing the petrogenetic-tectonic model outlined in this report.

Top diagram illustrates an incipient fracture system through crustal rocks of unspecified thickness and inhomogeneity. The middle diagram schematically illustrates the development of funnel-shaped void space by lateral displacement and subsequent filling by a magma which produced magnetically reversed lavas, (nsvr), minor hypabyssal dikes and sills (black heavy lines), and a series of gravity segregated rocks — peridotite (P), anorthositic rocks (a), and felsic rocks (f). Emplacement and cooling in this magmatic system was affected by foundering of a keystone block as shown. The lower diagram schematically shows further development of the same processes as described above, except that the rocks of the earlier magma series were involved in the tectonism as shown. The second periods of magma emplacement produced a series of magnetically normal lavas (nsvn), a chemically and tectonically distinct suite of hypabyssal rocks (not shown), and a troctolitic-gabbroic series of layered rocks (t). Note the foundering of the axial block during the second stage of magma emplacement tilts the rocks formed during the first stage. This process could have been continuous or intermittent during both stages. Furthermore, igneous rocks could have been emplaced along right hand side of the keystone blocks as shown in Figure 13.

Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO_2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Al_2O_3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Fe_2O_3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FeO	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MgO	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CaO	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Na_2O	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
K_2O	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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P_2O_5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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H_2O^-	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Q	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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Table 1. Chemical analyses of selected rocks from the Duluth Complex and possible parent magma compositions.

NOTES — TABLE 1

Anorthositic Series

1. Probably from an inclusion of anorthositic series rocks in the troctolitic-gabbroic rocks at Duluth. Sec. 19, T. 50N., R.14W., north of Proctor, Grout 1919f, p. 646.

Troctolitic-gabbroic Series

2. Layered troctolite M 4634 at Bardons Peak, Duluth, S.W. ¼ Sec. 34, T.6-N., R. 15W., Taylor 1964, p. 29.

3. Serpentinized troctolite M6933, Bald Eagle Intrusion, new analysis, N.E. ¼, Sec. 10, T.61N., R.10W.

4. Olivine gabbro, M6505, Bald Eagle Intrusion, new analysis, S.E. ¼ Sec. 11, T.61N., R.10W.

5. Oxide gabbro, M6971, Bald Eagle Intrusion, new analysis S.E., ¼ Sec. 29, T.59N., R.10W.

6. Anorthositic troctolite, M6150, South Kawishiwi Intrusion, new analysis N E. ¼, Sec. 13, T.61N., R.11W.

Analysis 3-6 made by instrumental and wet chemical methods by Kikumatsu Ohta, Director — Tokyo Coal and Mineral Laboratory, Tokyo, Japan.

Felsic Series

7. Granophyre, M6865, Greenwood Lake, new analysis, N W. ¼ Sec. 25, T.58N., R.11W.

8. Granophyre, M4628, Bardons Peak, Sec. 27, T.49N., R.15W.

9. Granophyric, aplitic granite, M3787 Duluth, N W. ¼ Sec. 27, T.50N., R 14W., Taylor, 1964, p. 42

10. Granophyre, M3764, Duluth, Sec. 32, T.50N., R.14W., Taylor, 1964, p. 42.

11. Ferrogranodiorite, M4624 Duluth N.W. ¼, Sec. 28, T 50N , R.4W., Taylor, 1964, p. 32.

Peridotite

12. Peridotite, Duluth, S.W. ¼, Sec. 34, T.49N., R.15W , Grout 1918f, p. 646.

Hornfels

13. Basalt hornfels, M3763, Duluth, northwest of 57th Ave. Quarry, Taylor, 1964, p. 13.

Possible Parent Magma Compositions

14. Augite, porphyritic basalt flow A, N.W. ¼, Sec. 20, T.49N., R.15W., Kilburg, 1972, table 3, p. 25
15. Chilled margin, Pigeon Point Sill, PP-219-3, N.W. ¼, Sec. 28, T.64N., R.7E., Mudrey, 1973, p. 129.
16. Basaltic komatiite Barberton type #3, Viljoen and Viljoen, 1969, p. 80, table 5.
17. Chilled margin, Skaergaard Intrusion, E.G. 4507, Wager and Brown, 1967, p. 152.

Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Unit	Anorthositic Series							Peridotite			Troctolitic-Gabbroic Series				
Mineral	Plagioclase		Clinopyroxene		Ilmenite		Biotite	Cpx	Ilm	Oliv	Plagioclase				
SiO_2	53.81	51.74	50.38	50.56	0.21	0.25	35.70	51.70	0.10	35.10	51.55	54.34	51.60	52.81	52.10
Al_2O_3	30.27	29.16	3.06	1.54	4.07	0.45	11.70	3.89	0.10	0.05	29.88	29.43	31.58	30.30	29.67
FeO	0.26	0.66	11.40	14.29	46.10	49.31	25.30	10.30	45.78	38.40	1.03	0.34	1.27	1.99	–
MgO	0.65	–	10.90	11.16	6.58	0.14	6.20	14.70	2.43	26.30	–	–	–	0.06	0.10
CaO	11.39	12.26	20.50	20.51	0.83	0.16	0.05	19.93	0.10	0.26	11.71	11.59	12.8	13.02	12.62
Na_2O	5.29	4.32	–	–	–	–	0.05	0.23	–	–	3.92	3.94	4.22	3.43	2.71
K_2O	0.33	0.38	–	–	–	–	9.13	–	–	–	0.41	0.35	0.35	0.26	0.30
TiO_2	0.04	0.03	0.31	0.47	50.58	47.31	10.13	1.32	50.20	0.11	0.10	0.11	0.08	0.10	0.16
MnO	0.01	–	0.35	0.34	0.66	0.64	0.07	0.19	0.54	0.32	0.00	0.00	–	–	–
Cr_2O_3	0.01	–	0.05	–	0.13	0.01	0.04	0.24	0.37	0.12	0.00	0.00	–	–	–
NiO	–	–	0.03	0.04	–	–	–	0.025	–	0.092	–	–	–	–	–
Total	101.4	98.31	96.90	98.91	98.06	98.27	98.75	100.295	99.56	100.657	99.27	100.22	[illegible]	101.99	97.73
Atoms															
O	16.00	16.00	6.00	6.00	6.00	6.00	22.00	6.00	6.00	4.00	32.00	32.00	32.00	32.00	32.00
Si	9.683	9.374	1.951	1.952	0.020	0.012	5.700	1.925	–	0.986	9.176	9.991	9.344	9.468	5.626
Ti	0.005	0.004	0.009	0.014	1.950	1.850	1.212	0.037	1.916	0.002	0.016	0.031	0.011	0.013	0.021
Al	6.383	6.361	0.141	0.470	3.004	0.020	2.291	0.051	–	–	6.464	6.316	6.722	6.484	6.432
Cr	–	–	–	–	0.066	0.000	0.004	0.007	0.015	0.003	–	–	–	–	–
Fe	0.039	0.048	0.370	0.461	1.989	2.144	3.377	0.321	1.939	0.901	0.292	0.051	0.152	0.291	–
Mn	0.002	–	0.012	0.011	0.029	0.028	0.008	0.006	0.023	0.008	–	–	–	–	–
Mg	0.013	–	0.631	0.642	0.038	0.011	1.473	0.816	0.164	1.102	–	–	–	0.011	0.026
Ca	2.164	2.427	0.853	0.848	0.002	0.008	0.400	0.778	–	0.085	2.309	2.261	2.327	2.501	2.498
Ni	–	–	0.001	0.001	–	–	–	0.001	–	0.002	–	–	–	–	–
Na	1.835	1.550	–	–	–	–	0.148	0.017	–	–	1.399	0.700	1.461	1.93	0.971
K	0.075	0.090	–	–	–	–	1.869	–	–	–	0.096	0.042	0.081	0.064	0.077
Total	20.342	20.074	3.960	4.00	4.07	4.081	15.916	3.998	4.077	3.010	20.039	19.292	20.319	19.958	19.661

Number	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Unit	Troctolitic-Gabbroic Series													
Mineral	Olivine					Clinopyroxene					Orthopyroxene		Ilmenite	
SiO_2	35.19	35.75	35.21	35.50	36.25	49.28	52.64	51.11	50.31	52.05	51.06	55.51	0.09	0.27
Al_2O_3	0.12	0.00	–	–	–	1.95	1.52	1.89	1.69	1.14	0.62	0.74	0.02	0.21
FeO	38.58	36.76	35.82	38.17	34.58	11.64	8.96	9.97	10.84	9.97	22.10	20.31	43.57	49.69
MgO	23.98	27.50	27.97	26.30	29.31	14.57	14.31	16.27	13.06	14.96	21.57	25.06	1.53	1.86
CaO	0.05	0.04	0.06	0.04	0.04	19.44	20.93	21.44	20.33	20.70	1.11	1.27	0.03	0.02
TiO_2	0.01	0.01	–	0.05	–	0.81	0.53	0.43	0.57	0.47	0.21	0.28	48.87	49.29
MnO	0.67	0.47	0.46	0.50	0.48	0.54	0.27	0.26	0.28	0.26	0.56	0.62	0.46	0.64
Cr_2O_3	0.01	0.01	0.01	–	0.05	0.19	0.11	–	0.06	0.15	0.04	0.09	0.18	0.19
NiO	0.11	–	0.17	0.20	0.16	0.01	0.07	0.06	0.07	0.06	0.01	0.07	–	–
Total	98.72	100.54	99.70	100.76	100.87	98.47	99.36	101.43	97.21	100.06	97.28	103.95	94.79	101.97
Atom														
O	4.00	4.00	4.00	4.00	4.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Si	1.010	0.995	0.987	0.994	0.995	1.893	1.966	1.893	1.946	1.944	1.965	1.969	0.002	0.008
Ti	0.000	0.000	–	0.001	–	0.006	0.015	0.012	0.017	0.013	0.006	0.007	1.853	1.856
Al	0.004	–	–	–	–	0.090	0.067	0.083	0.077	0.064	0.028	0.031	–	0.006
Cr	0.000	0.000	0.000	–	0.001	0.006	0.003	–	0.002	0.004	0.001	0.003	0.003	0.008
Fe	0.926	0.856	0.840	0.894	0.794	0.374	0.280	0.309	0.351	0.311	0.711	0.603	1.936	2.082
Mn	0.016	0.011	0.011	0.012	0.011	0.018	0.009	0.008	0.009	0.008	0.018	0.019	0.021	0.028
Mg	1.026	1.141	1.169	1.098	1.199	0.834	0.799	0.898	0.753	0.833	1.237	1.325	0.121	0.139
Ca	0.002	0.001	0.002	0.001	0.001	0.800	0.839	0.851	0.842	0.829	0.046	0.048	–	0.007
Na	–	–	–	–	–	–	–	–	–	–	–	–	–	–
K	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ni	0.003	–	0.006	0.005	0.004	0.000	0.002	0.002	0.002	0.002	0.000	0.002	–	–
Total	2.987	3.005	3.013	3.005	3.005	4.037	3.982	4.054	3.998	4.009	4.012	4.007	4.041	4.128

Table 2. Selected mineral analyses from different units of the Duluth Complex.

NOTES: All analyses are averages of triplicate electron microprobe point analyses made in general on the centers of grains. Analyzing conditions: 20 K.V., 0.03 microamperes, 5-10 micrometer diameter electron beam. X-ray intensity data was corrected for background and reduced with analyzed mineral standards All analyses were made on the M.A.C. Model 400 electron microprobe in the Department of Geology and Geophysics, University of Minnesota. Analyses from Beitsch (in prep).

Analyses	Sample #
1, 3, & 5	312
2, 4, & 6	222
7	303
8, 9, & 10	DC-2
11, 16, 21, 26, & 28	124
12, 17, 22, 27, & 29	156
13, 18, & 23	50
14, 19, & 24	180
15, 20, & 25	321

Location

S.E. ¼ Sec. 10, T.64N., R.5W.
S.E. ¼ Sec. 8, T.64N., R.5W.
S W. ¼ Sec. 23, T.64N., R.5W.
S.W. ¼ Sec. 34, T.49N., R.15W.
S.E. ¼ Sec. 34, T.65N., R.5W.
S.E. ¼ Sec 32, T.65N., R.5W.
S.E. ¼ Sec. 3, T.64N., R.5W.
N.E. ¼ Sec. 32, T.65N., R.5W.
N.W. ¼ Sec. 11, T.64N., R.5W.

	Analysis Table	No	Calculated Chemical Mode	
Parent Magma		14		
Rock Type				
[illegible]granophyre	1	9	8.01	12.33
[illegible]-granophyre	1	10	4.32	
Anorthositic gabbro	1	1	21.53	
Peridotite				
Olivine	2	10	16.18	[illegible]
Clinopyroxene	2	8	45.44	
Ilmenite	2	9	3.90	

Summary: 12% granophyre + 22% anorthositic gabbro + 65% peridotite = basal lava composition of magnetically reversed lava (Table 1-14)

	Analysis Table	No	Calculated Chemical Mode
Parent Magma	1	15	
Rock Type			
Troctolite	1	3	18.47
Olivine gabbro	1	4	15.14
Oxide gabbro	1	5	16.43
Troctolite & norite			
Olivine	2	16	9.25
Plagioclase	2	11	37.74
Orthopyroxene	2	26	10.03

Summary: 18% troctolite + 15% olivine gabbro + 16% oxide gabbro + 50% troctolite and norite = chilled margin composition of Pigeon Point sill (Table 1-15)

Example of Best Fit Calculation for Low-Al Magma Type[1]

Oxide	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	MnO
Actual	49.05	8.55	13.53	11.31	12.11	2.04	.91	1.97	.18
Computed	49.21	8.75	13.25	11.56	11.42	1.23	.48	2.17	.17
Difference	-.161	-.192	.275	-.245	.345	.809	.429	-.183	.026
Squared Weight	.16	.36	.49	.49	.49	1.00	1.00	.64	.49
Percent Diff	-.33	-2.25	2.07	-2.16	2.91	39.70	47.32	-9.21	14.28

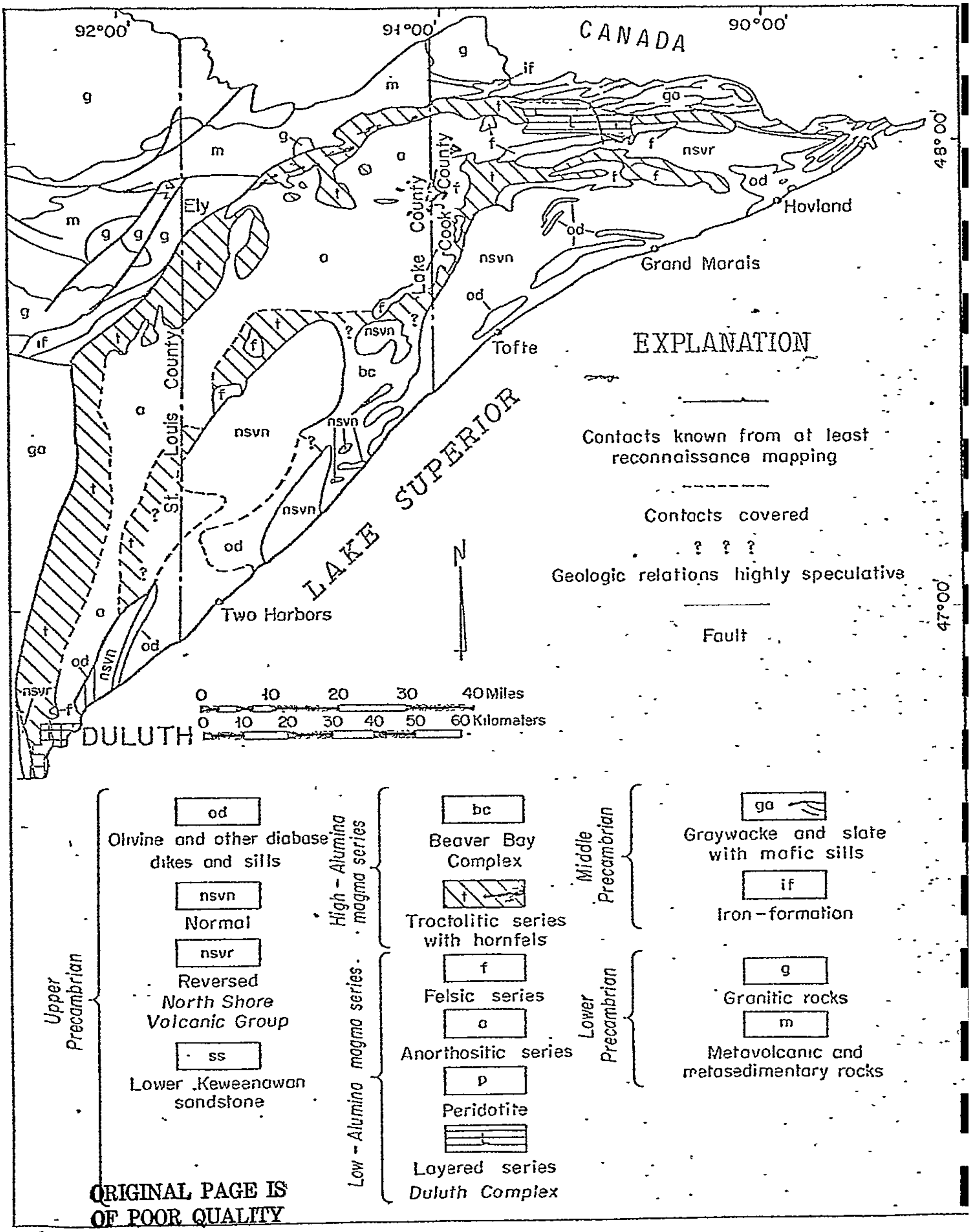
Example of Best Fit Calculation for High-Al Magma Type[2]

Oxides	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	MnO
Actual	48.02	16.46	11.21	8.57	9.54	2.60	.33	1.02	.16
Computed	48.03	16.46	11.23	8.55	9.53	2.45	.35	1.02	.19
Difference	-.014	-.026	-.011	.016	-.005	.154	-.019	-.001	-.025
Squared Weight	.16	.16	.36	.64	.64	.64	1.64	1.00	.36
Percent Diff	-.01	-.11	-.10	.19	-.05	5.98	-5.55	-.05	-15.62

Table 3. Summary of mass balance calculations on possible parent magma compositions for different units in the Duluth Complex.

NOTES: Summary equations give results for mass balance calculations for low-Al and high-Al magma compositions. The analyses of units or minerals used to calculate a least squares mass balance (Wright & Doherty, 1970) for the magma compositions are tabulated at the top of the table. The results of the calculations are tabulated at the bottom. See text for discussion.

1. The errors in the fit for this calculation are all within the analytical error of the individual analyses except for Na and K. Higher Na and K concentrations in the granophyre or lower concentrations in the parent magma would be required for a better fit.
2. The errors in the fit for this calculation are all within the analytical error of the individual analyses.



92°00'
91°00'
90°00'
CANADA
48°00'
47°00'
Ely
Hovland
Grand Marais
Tofte
Two Harbors
DULUTH
LAKE SUPERIOR
St. Louis County
Lake County
Cook County
N
0 10 20 30 40 Miles
0 10 20 30 40 50 60 Kilometers
EXPLANATION
Contacts known from at least reconnaissance mapping
Contacts covered
? ? ?
Geologic relations highly speculative
Fault
Upper Precambrian
od
Olivine and other diabase dikes and sills
nsvn
Normal
nsvr
Reversed
North Shore Volcanic Group
ss
Lower Keweenawan sandstone
High - Alumina magma series
bc
Beaver Bay Complex
t
Troctolitic series with hornfels
Low - Alumina magma series
f
Felsic series
a
Anorthositic series
p
Peridotite
Layered series
Duluth Complex
Middle Precambrian
ga
Graywacke and slate with mafic sills
if
Iron-formation
Lower Precambrian
g
Granitic rocks
m
Metavolcanic and metasedimentary rocks

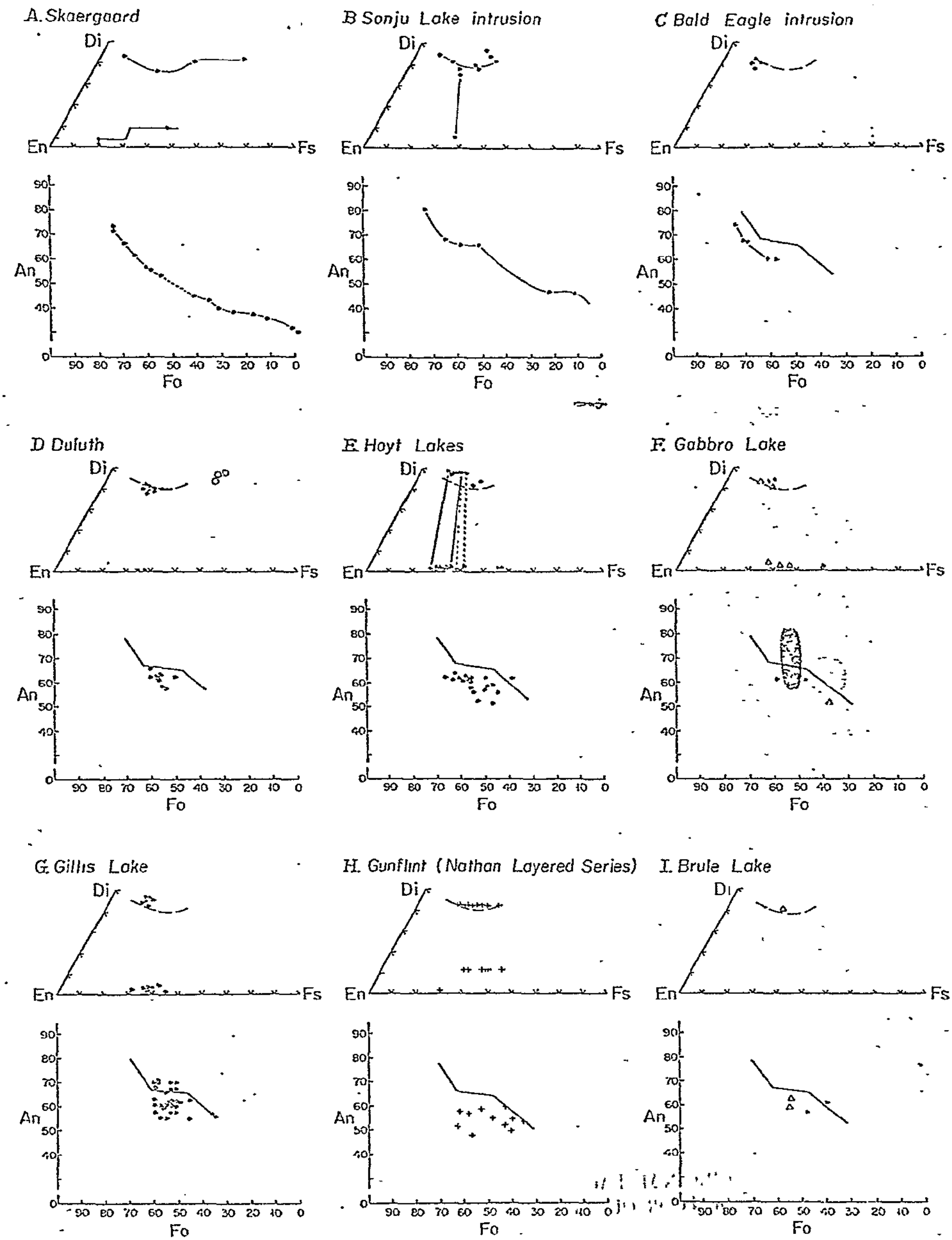

A. Skaergaard
B Sonju Lake intrusion
C Bald Eagle intrusion
D Duluth
E Hoyt Lakes
F Gabbro Lake
G Gillis Lake
H. Gunflint (Nathan Layered Series)
I. Brule Lake
Di
En
Fs
An
Fo
0
40
50
60
70
80
90
0 10 20 30 40 50 60 70 80 90

Table 1.

Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO_2	49.39	47.36	43.10	49.81	43.24	47.75	73.45	64.29	73.55	77.75	53.78	32.90	41.31	47.65	47.40	53.75	48.08
Al_2O_3	29.00	19.81	28.84	15.77	15.62	23.62	12.15	14.44	12.05	12.71	16.34	1.59	12.12	0.31	10.20	10.02	17.22
Fe_2O_3	0.34	1.30	2.11	0.64	3.37	0.43	2.67	2.83	2.37	0.39	4.66	13.25	3.52	1.49	0.83	1.25	1.32
FeO	2.89	10.65	5.79	6.61	11.57	7.29	1.69	3.54	1.09	0.47	7.65	21.06	14.57	11.80	10.32	9.90	0.44
MgO	2.26	8.59	13.37	8.82	6.62	5.89	0.38	1.76	0.51	0.34	1.31	20.14	6.58	10.09	8.46	10.30	8.67
CaO	13.06	9.33	9.17	14.63	10.62	9.03	0.67	1.03	0.76	0.69	7.00	0.50	11.07	11.34	9.44	10.10	11.38
Na_2O	3.89	2.94	1.74	3.27	2.56	3.13	3.99	4.03	2.85	6.24	4.07	tr	2.06	1.98	2.57	2.70	2.37
K_2O	0.10	0.42	0.37	0.43	0.55	0.67	3.91	4.44	5.40	0.40	1.76	tr	0.16	0.88	0.33	0.47	0.25
TiO_2	-	1.10	0.17	0.47	3.26	0.39	0.32	0.71	0.27	0.21	1.55	5.36	7.04	1.93	1.01	0.87	1.17
P_2O_5	0.09	0.11	0.04	0.34	0.03	0.06	0.05	0.15	0.05	0.01	0.54	tr	0.63	0.23	0.065	-	0.10
MnO	0.03	0.14	0.13	0.13	0.17	0.11	0.04	0.07	0.05	0.01	0.18	0.40	0.21	0.19	0.16	0.22	0.10
BaO	-	-	-	-	-	-	-	0.09	0.07	-	-	-	-	-	-	-	-
CO_2	-	0.01	0.02	0.00	0.08	0.07	0.02	0.01	0.10	0.40	0.03	0.10	0.05	0.44	0.01	-	-
SrO	-	0.01	-	-	-	-	-	0.02	0.01	-	0.04	0.00	-	-	-	-	-
S	-	-	-	-	-	-	-	0.01	0.01	-	-	0.05	0.10	-	-	-	-
$-H_2O$	0.09	0.05	-	-	-	-	-	0.95	0.09	0.13	0.32	0.55	0.06	-	0.09	-	0.05
$+H_2O$	0.34	0.24	4.00	0.15	0.29	0.25	0.76	1.21	0.38	0.38	0.65	4.56	0.44	1.92	0.46	-	1.01
Total	100.53	100.06	99.85	99.77	99.88	99.04	99.60	99.60	99.67	100.12	99.96	100.46	99.92	99.65	99.79	99.66	100.17
Q	-	-	-	-	-	-	33.38	18.10	35.30	41.17	6.50	-	-	-	-	-	-
C	0.60	-	-	-	-	-	0.30	1.46	0.57	1.73	-	0.91	-	-	-	-	-
Ne	-	-	-	1.15	0.64	1.06	-	-	-	-	-	-	-	-	-	-	-
OR	0.59	2.48	2.19	2.54	3.25	3.98	23.11	26.24	31.91	2.36	10.40	-	0.95	5.20	1.95	2.78	1.48
Ab	24.45	24.75	14.49	17.09	19.41	23.85	33.52	33.60	22.21	40.03	31.31	-	16.04	11.51	21.63	22.85	20.05
An	64.20	36.95	42.63	31.57	30.07	49.17	3.00	4.35	3.60	3.31	34.08	2.48	23.87	13.97	37.21	13.03	35.61
Hyp	6.11	4.95	0.16	-	-	-	1.39	7.40	1.27	1.06	6.72	47.28	8.00	15.19	7.69	25.94	7.72
Diop	-	-	2.08	33.00	16.31	0.21	-	-	-	-	8.86	-	22.25	35.29	7.58	23.09	16.43
Ol	3.40	23.35	30.69	12.36	12.91	20.05	-	-	-	-	-	16.12	6.59	9.15	13.45	0.92	13.40
Mt	0.49	1.88	3.06	0.93	4.74	0.63	3.87	4.10	2.26	0.57	6.76	19.21	5.10	2.16	1.20	1.81	1.91
Ilm	-	2.09	0.32	0.09	9.99	0.75	0.61	1.35	0.51	0.40	2.94	10.18	13.37	3.67	1.92	1.65	2.22
Ap	0.21	0.26	0.09	0.09	0.05	0.14	0.12	0.35	0.12	0.02	1.25	-	1.46	0.53	0.14	-	0.23
Cal	-	0.02	0.05	-	0.20	0.16	0.05	0.05	0.36	0.91	0.07	0.23	0.11	1.00	0.02	-	-
Mg	59.00	62.00	80.00	72.00	68.00	60.00	74.00	65.00	100.00	84.00	35.00	77.00	53.00	67.00	62.00	68.00	69.00

Table 2.

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NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
UNIT	ANORTHOSITIC SERIES							PERIDOTITE			TROCTOLITIC-GABBROIC SERIES				
MINERAL	Plagioclase		Clinopyroxene		Ilmenite		Biotite	Cpx	Ilm	Oliv	Plagioclase				
SiO_2	53.81	51.74	50.30	50.55	0.21	0.25	35.70	51.70	0.10	35.10	51.50	54.34	51.10	52.81	52.10
Al_2O_3	30.27	29.16	3.06	1.54	0.07	0.45	11.70	2.09	0.10	0.05	29.60	29.43	31.50	30.30	29.67
FeO	0.26	0.44	11.40	14.29	46.10	49.31	25.30	10.30	45.70	38.40	1.83	0.34	1.27	1.99	-
MgO	0.05	-	10.90	11.16	0.50	0.14	6.20	14.70	2.43	26.30	-	-	-	0.06	0.10
CaO	11.29	12.24	20.50	20.51	0.03	0.16	0.05	19.50	0.10	0.16	11.71	11.59	12.0	13.02	12.61
Na_2O	5.29	4.32	-	-	-	-	0.45	0.23	-	-	3.92	3.96	4 22	3.43	2.71
K_2O	0.33	0.38	-	-	-	-	9.13	-	-	-	0.41	0.35	0.35	0.20	0.30
TiO_2	0.04	0.03	0.31	0.47	50.50	47.31	10.11	1.32	50.20	0.11	0.10	0.11	0.08	0.10	0.16
MnO	0.01	-	0.35	0.34	0.46	0.64	0.07	0.19	0.54	0.32	0.00	0.00	-	-	-
Cr_2O_3	0.01	-	0.05	-	0.13	0.01	0.04	0.24	0.37	0.12	0.00	0.00	-	-	-
NiO	-	-	0.03	0.04	-	-	-	0.025	-	0.092	-	-	-	-	-
Total	101.4	98.31	95.90	98.91	98.00	98.27	98.75	100.295	99.54	100.657	99.27	100.12	100.82	101.99	97.73
ATOMS															
O	16.00	16.00	6.00	6.00	6.00	6.00	23.00	6.00	6.00	4.00	32.00	32.00	32.00	32.00	32.00
Si	9.625	9.574	1.951	1.952	0.010	0.012	5.700	1.925		0.986	9.476	9.831	9.304	9.468	9.624
Ti	0.005	0.004	0.009	0.014	1.958	1.850	1.213	0.037	1.915	0.002	0.014	0.031	0.011	0.013	0.021
Al	6.303	6.361	0.141	0.070	0.004	0.028	2.203	0.091	-	-	6.464	6.316	6.722	6.404	6.452
Cr	-	-	-	-	0.006	0.000	0.004	0.007	0.015	0.003	-	-	-	-	-
Fe	0.039	0.068	0.370	0.461	1.988	2.144	3.377	0.321	1.939	0.903	0.282	0.051	0.192	0.298	-
Mn	0.002	-	0.012	0.011	0.020	0.028	0.008	0.006	0.023	0.008	-	-	-	-	-
Mg	0.013	-	0.631	0.642	0.038	0.011	1.473	0.816	0.104	1.102	-	-	-	0.016	0.026
Ca	2.164	2.427	0.853	0.848	0.002	0.008	0.005	0.778	-	0.005	2.309	2.261	2.327	2.501	2.490
Ni	-	-	0.001	0.001	-	-	-	0.001	-	0.002	-	-	-	-	-
Na	1.835	1.550	-	-	-	-	0.140	0.017	-	-	1.399	0.700	1.481	1.192	0.971
K	0.075	0.099	-	-	-	-	1.860	-	-	-	0.096	0.042	0.031	0.064	0.077
Total	20.142	20.074	3.969	4.00	4.026	4.081	15.986	3.998	4.077	3.010	20.039	19.292	20.119	19.958	19.661

NUMBER	16	17	18	19	20	21	22	23	24	25	26	27	28	29
UNIT	TROCTOLITIC-GABBROIC SERIES													
MINERAL	Olivine					Clinopyroxene					Orthopyroxene		Ilmenite	
SiO_2	35.19	35.75	35.21	35.50	36.25	49.28	52.64	51.11	50.31	52.05	51.06	55.51	0.09	0.17
Al_2O_3	0.12	0.00	-	-	-	1.99	1.52	1.89	1.69	1.44	0.62	0.74	0.00	0.11
FeO	38.58	36.75	35.82	38.17	34.58	11.64	8.96	9.97	10.84	9.97	22.10	20.31	43.57	49.69
MgO	23.98	27.50	27.97	26.30	29.31	14.57	14.33	16.27	13.06	14.96	21.57	25.06	1.53	1.86
CaO	0.05	0.04	0.06	0.04	0.04	19.44	20.93	21.44	20.33	20.70	1.11	1.27	0.00	0.02
TiO_2	0.01	0.01	-	0.05	-	0.81	0.53	0.43	0.57	0.47	0.21	0.28	48.87	49.29
MnO	0.57	0.47	0.46	0.50	0.48	0.54	0.27	0.26	0.22	0.26	0.56	0.62	0.46	0.64
Cr_2O_3	0.01	0.01	0.03	-	0.05	0.19	0.11	-	0.06	0.15	0.04	0.09	0.18	0.19
NiO	0.11	-	0.17	0.20	0.16	0.01	0.07	0.06	0.07	0.06	0.01	0.07	-	-
Total	98.72	100.54	99.70	100.76	100.87	98.47	99.36	101.43	97.21	100.06	97.26	103.95	94.70	101.97
ATOM														
O	4.09	4.00	4.00	4.00	4.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Si	1.010	0.995	0.987	0.994	0.995	1.892	1.968	1.893	1.946	1.944	1.965	1.969	0.002	0.008
Ti	0.000	0.000	-	0.001	-	0.006	0.015	0.012	0.017	0.013	0.005	0.007	1.953	1.856
Al	0.004	-	-	-	-	0.090	0.067	0.083	0.077	0.064	0.028	0.031	-	0.005
Cr	0.000	0.000	0.000	-	0.001	0.006	0.003	-	0.002	0.004	0.001	0.003	0.003	0.008
Fe	0.926	0.856	0.840	0.893	0.794	0.374	0.280	0.309	0.351	0.311	0.711	0.603	1.936	2.082
Mn	0.016	0.011	0.011	0.012	0.011	0.018	0.009	0.003	0.009	0.008	0.018	0.019	0.021	0.028
Mg	1.026	1.141	1.169	1.098	1.199	0.834	0.799	0.898	0.753	0.833	1.237	1.325	0.121	0.138
Ca	0.002	0.001	0.002	0.001	0.001	0.800	0.839	0.851	0.842	0.829	0.046	0.048	-	0.002
Na	-	-	-	-	-	-	-	-	-	-	-	-	-	-
K	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ni	0.003	-	0.004	0.005	0.004	0.000	0.002	0.002	0.002	0.002	0.000	0.002	-	-
Total	2.987	3.005	3.013	3.005	3.005	4.037	3.932	4.054	3.998	4.009	4.012	4.007	4.041	4.128

Table 3.

	Analysis Table	No.	Calculated Chemical Mode	
Parent Magma	1	14		
Rock Type				
Na-granophyre	1	9	8.01	12.33
K-granophyre	1	10	4.32	
Anorthositic gabbro	1	1	21.52	
Peridotite				
Olivine	2	10	16.18	64.82
Clinopyroxene	2	8	45.64	
Ilmenite	2	9	3.00	

Summary: 13% granophyre + 22% anorthositic gabbro + 65% peridotite = basal lava composition of magnetically reversed lavas (Table 1-14).

	Analysis Table	No.	Calculated Chemical Mode
Parent Magma	1	15	
Rock Type			
Troctolite	1	3	10.47
Olivine gabbro	1	4	15.14
Oxide gabbro	1	5	16.43
Troctolite & norite			
Olivine	2	16	9.25
Plagioclase	2	11	37.74
Orthopyroxene	2	26	10.83

Summary: 10% troctolite + 15% olivine gabbro + 16% oxide gabbro + 58% troctolite and norite = chilled margin composition of Pigeon Point sill (Table 1-15).

Example of Best-Fit Calculation for Low-Al Magma Type[1]

Oxides	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	MnO
Actual	49.05	8.55	13.53	11.31	12.19	2.04	.91	1.99	.20
Computed	49.21	8.75	13.25	11.56	11.82	1.23	.48	2.17	.17
Difference	-.161	-.192	.275	-.245	.365	.809	.429	-.183	.028
Squared Weight	.36	.36	.49	.49	.49	1.00	1.00	.64	.49
Percent Diff	-.33	-2.25	2.03	-2.16	2.99	39.70	47.32	-9.21	14.28

Example of Best-Fit Calculation for High-Al Magma Type[2]

Oxides	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	MnO
Actual	48.02	10.44	11.21	8.57	9.56	2.60	.33	1.02	.16
Computed	48.03	10.46	11.23	8.55	9.57	2.45	.35	1.02	.19
Difference	-.006	-.020	-.011	.016	-.005	.154	-.019	-.001	-.025
Squared Weight	.36	.36	.36	.64	.64	.64	1.00	1.00	.36
Percent Diff	-.01	-.11	-.10	.19	-.05	5.90	-5.55	-.05	-15.62

APPENDIX II

Minerals and Plate Tectonics: A Conceptual Revolution

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Minerals and Plate Tectonics: A Conceptual Revolution

Drastically higher prices for oil and declining U.S production have drawn attention to supplies of other key industrial materials, especially minerals Although immediate shortages do not appear likely, some authorities have expressed concern about the extent of U.S. dependence on other countries for supplies of chromium, manganese, and other metals. Moreover, depletion of high grade ores and environmental regulations affecting mining and ore processing are expected to increasingly constrain the availability of minerals.

Fortunately, renewed interest in minerals comes at a time of excitement and sweeping new ideas in the study of mineral deposits. The new ideas reflect the impact on economic geology of plate tectonic models for the evolution of the earth's crust. Many ore deposits, for example, are now known to occur at present or past boundaries of the huge crustal plates whose movements have shaped and reshaped the earth's surface. What ores are formed and where they are placed in the crust, it is proposed, depend principally on the tectonic history of a particular region; several models of the processes involved have been put forward. Similarly, it is proposed that the interaction of seawater with cooling volcanic rock is the principal means by which many metals are extracted and concentrated into economically valuable ore bodies; thus hydrothermal rather than magmatic processes are the key to understanding the geochemistry of ore deposits. These proposals and others have stimulated a host of more detailed investigations. Many geologists believe that these developments portend a fundamentally new understanding of the origin of minerals and are laying the scientific foundation for a new era in mineral exploration.

Not all mineral deposits fit the new conceptual framework, but many major classes of metal ores are explicable in its terms. The evolving theoretical models provide detailed if still controversial explanations for the chemistry, mineralogy, and stratigraphic location of these deposits and thus a host of clues with which to look for still undiscovered mineral deposits, some of which are finding tentative use in the mineral industry. They also have implications for the evolution of the earth's crust; similarities between recent and more ancient ore bodies are seen by some researchers as evidence that tectonic processes not unlike those of the present geologic era occurred throughout most of geologic history.

Many metallic ores are now widely recognized to be of volcanic origin in the sense that they occur in volcanic or igneous rocks and were formed at the same time as those rocks. According to plate tectonic theory, volcanism occurs in several circumstances: at diverging plate boundaries (mid-ocean ridges or other centers of seafloor spreading), where mantle material rises to form new oceanic crust; at converging boundaries, where crustal plates descend into the mantle in a process known as subduction, leading to volcanism that forms chains of mountains or oceanic island arcs; and, less frequently, over hot spots caused by ascending plumes of mantle material (Fig. 1). Each of these processes, except possibly the last, is now thought to give rise to a characteristic type or types of ore deposits.

One of the clearest examples—and one which has had major impact on the thinking of economic geologists—is found on the Mediterranean island of Cyprus, long a rich source of copper. The copper sulfide ore occurs in the Troodos area of Cyprus in a distinctive sequence of rocks: on top, sediments of a type formed on the ocean floor; beneath the sediments, pillow lavas formed when molten volcanic material erupts into seawater; farther down, vertical sheets or dikes of basaltic rocks formed as rifts or cracks in the ocean floor are filled from below with volcanic material, and on the bottom, ultramafic rocks (rich in magnesium and iron) that are believed to be characteristic of the earth's mantle. This progression of rock types is known to geologists as an ophiolitic sequence. About the time that economic geologists recognized copper sulfide deposits as an integral part of these rocks on Cyprus, other geologists recognized the ophiolitic sequence as exactly that which should be formed at a mid-ocean ridge. Thus the Troodos area is now thought to be a largely unaltered piece of oceanic crust thrust up when Cyprus was formed, and the mineral deposits it contains are thought to be characteristic of those formed at mid-ocean ridges.

The minerals include sulfides of copper, iron, and sometimes zinc embedded in the pillow lavas, small masses or "pods" of chromium ore near the top of the ultramafic layer, and asbestos deposits, also in the ultramafic rock. Although not present on Cyprus, lateritic nickel deposits are sometimes found in sections of oceanic crust where ultramafic rock (which is rich in nickel) has been exposed and weathered. Mineral deposits of the Troodos type are found in many parts of the world, including the northeastern United States and eastern Canada. They range in age from the geologically young deposits of Cyprus to older deposits that originated as many as 600 million years ago.

A second major type of mineral deposits—large bodies of low grade ores known as porphyry coppers—are commonly associated with converging plate boundaries. A prime example is the extensive copper deposits in the Andes, where the eastward-moving oceanic crust of the Pacific plunges under the lighter material of the westward-moving South American continent. Partial melting of the downward-moving oceanic plate is believed to generate magmas that rise through the overlying continental rocks, sometimes reaching the surface to form volcanoes. The upper portions of the pipelike stalks or cores of these magmatic intrusions into the surrounding continental rock often contain copper and molybdenum, and sometimes gold and silver as well. Several investigators have studied this process, including Richard Sillitoe, formerly of the Instituto de Investigaciónes Geológicas, Santiago, Chile, and now at Imperial College, London; P. W. Guild of the U.S. Geological Survey, Reston, Virginia; Andrew Mitchell of Oxford University; and M. S. Garson of the Insti-

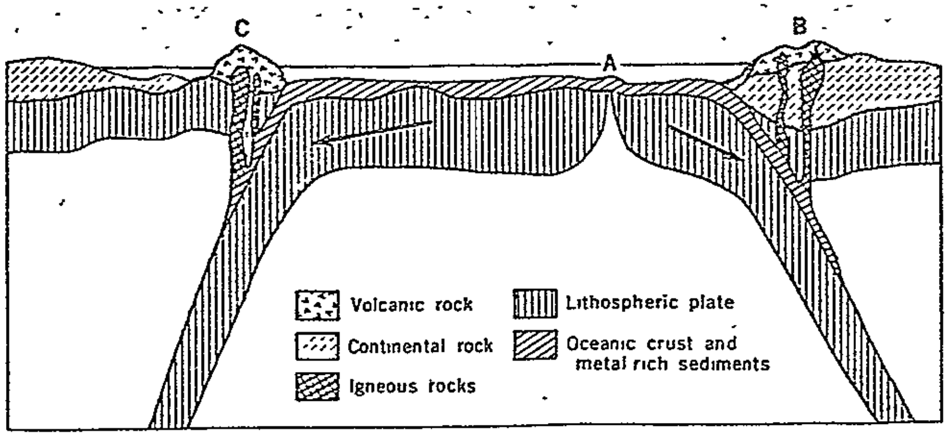

Fig. 1. Schematic showing three different ore-forming environments and the plate-tectonic phenomena postulated to give rise to them. (A) a mid-ocean ridge or rise; (B) a subduction zone underlying a continental margin; and (C) a subduction zone underlying an island arc. Arrows indicate direction of motion of the plates.

tute of Geological Sciences, London They propose that formation of porphyry ore deposits is a normal facet of the processes that generate the igneous rocks in which they occur. Sillitoe, for example, suggests that the metals of the porphyry ores were initially incorporated in oceanic crust at the mid-ocean ridge, transported horizontally by the movement of the plate, and then released as the downward-moving plate is heated

Porphyry copper deposits account for more than half the world's supply of that metal. In addition to the porphyry deposits in the Andes, there are deposits in western North America, in parts of the Alpine belt of Europe, and in Iran and Pakistan. Although normally associated with continental rocks, porphyry deposits are also found in some of the larger volcanic islands of the southwest Pacific. Most of these deposits are geologically youthful, less than 200 million years in age. Highly eroded remains of older deposits have been found, however, in northeast North America. Even in the richest porphyry ores, however, copper rarely exceeds 1 percent, and 0 5 percent is more common, so mining consequently involves extracting and processing large tonnages of ore. The association of porphyry deposits with the subduction of oceanic crust into the mantle and the concomitant magmatic activity is so strong that it has been the basis for exploration efforts. A major exception, however, may be the porphyry deposits in Arizona, which according to J. David Lowell of the University of Arizona do not show evidence of a subduction zone. In recent years new porphyry deposits have been found in Okinawa, Panama, and British Columbia.

Deposits of a third distinctive type, known as massive sulfides because they often occur as large, nearly pure lenses of high grade ore, are found in modern island arcs and some geologically older island arc materials that are now incorporated in continental margins These deposits, like the porphyry coppers, are associated with the convergence of two crustal plates. They are typically polymetallic, containing copper, zinc, lead, gold, and silver.

The prototype deposits for investigators unraveling the origin of these massive sulfides have been those in northeast Japan. This black "Kuroko" ore is thought to have been formed by submarine volcanic processes and deposited in shallow, nearshore environments late in the evolutionary history of a volcanic island chain. The volcanic rocks associated with these deposits are correspondingly highly evolved and often include fragments from explosive eruptions. Marine sediments are also often found with such deposits.

A second variety of massive sulfide ores—those of the Besshi type—are also found in island arcs. Besshi copper and iron sulfide ores (named after a deposit on Shikoku Island, Japan) are, like the Kuroko ores, commonly thought to be submarine volcanic emissions, but deposited on the underwater slopes of volcanoes early in their evolution. Still other classes or subclasses of island arc mineral deposits, corresponding to additional stages in the evolution of these fragments of land, can be distinguished. In fact, a model of the process proposed by Mitchell and J. D. Bell, also of Oxford University, describes seven such stages They give the timing and accompanying rock types for the forma-

Plate Tectonics: How Far Back?

The impact of plate tectonics on mineral geology is rapidly becoming a two-way relationship. Direct evidence from the sea floor for plate motions and related tectonic mechanisms exists only for the last 200 million years of the geologic record, but metallogenic and other geologic data support the idea that these phenomena extend back at least 600 million years. Thus mineral deposits indicative of crustal formation at mid-ocean ridges and of subduction of crustal material into the mantle to form volcanic island arcs and continental mountain belts are found throughout that period. The key question is what happened before 600 million years ago, in the Precambrian era that includes 80 percent of the earth's history.

Among the oldest rocks of Precambrian continental areas are the mineral-rich greenstone belts, which contain volcanic rocks resembling those of modern island arcs in both chemical composition and physical properties. Greenstone belts are found in Canada, Australia, South Africa, and other areas of very old crust. According to A. M. Goodwin of the University of Toronto, the proportions of basalt, andesite, and rhyolite in these ancient volcanic belts are similar to those in recent island arcs—about 60 percent basalt, 30 percent andesite, and 10 percent rhyolite. In both geologic settings the volcanic piles show a common stratigraphy—basaltic rocks on the bottom, andesite above them, and rhyolite on top. The Precambrian rocks also show evidence, he finds, of explosive volcanism, a characteristic of island arc volcanoes.

Mineral deposits in greenstone belts and in island arcs are quite similar too, especially those known as massive sulfide deposits (including copper, lead, and zinc ores) and the precious metal deposits that occur with them. These ores are widely believed to be of submarine volcanic origin in both Precambrian deposits and island arcs. The massive sulfide deposits are typically found embedded in rhyolitic rocks near the top of the volcanic pile, while gold, some observers believe, is commonly found lower in the volcanic sequence.

In view of these similarities, some researchers have proposed that Precambrian greenstone belts represent ancient island arcs. If correct, this view would imply that plate tectonic activity existed well back into the earth's early geologic history and that the formation of island arcs and their accretion to continents has continued for perhaps 3 billion years.

There are some substantial dissenting views, however. R. H. Ridler of the Geological Survey of Canada finds no evidence for large-scale horizontal movements of crust in the early Precambrian. He also points out that island arcs are typically asymmetric, reflecting their tectonic origin (with an oceanic trench on one side and a shallow basin on the other); greenstone belts, on the other hand, show a symmetry that he believes is more characteristic of development in a basin. R. W. Hutchinson of Western Ontario University distinguishes three types of massive sulfide mineral ores—two modern types and one characteristic of the ancient ores. In his view the ores are similar, but differ in ways that suggest an evolution of ore types. This reflects a corresponding evolution in tectonic mechanisms, away from some predecessor mechanism to plate tectonics, which formed the modern island arcs. In contrast, Andrew Mitchell and J. D Bell of Oxford University believe the evidence suggests that "ore-forming processes in [island] arcs have changed little during the last 2×10^9 years."

The debate is still wide open. But it is apparent that evidence from ancient mineral ores and the rocks in which they occur will play a central role It is a debate that investigators interested in the evolution of the earth's crust will watch with interest.—A.L.H.

tion of Besshi and Kuroko massive sulfides, porphyry coppers, and exogenous mineral deposits (those not formed at the same time as the surrounding volcanic rocks) found in island arcs.

As the plates move, island arcs may be swept into and incorporated in continental masses. And because continents collide, it is not surprising that island arc fragments have been identified in what are now continental interiors. This is significant because a second and major source of massive sulfide and precious metal deposits is the so-called greenstone belts found in ancient Precambrian areas of continents. These belts have historically been the source of much of the world's mineral wealth, with rich deposits ranging from iron ores, important gold deposits, copper and zinc to lead and silver ores.

The Precambrian mineral ores, like younger massive sulfide deposits, are believed to result from submarine volcanic processes. The volcanic rocks associated with these ancient mineral deposits also show chemical and mineralogical similarities to those of island arcs. Hence some geologists believe that greenstone belts represent ancient island arcs. Since some of the Canadian belts date back at least 3 billion years, this would imply the existence of tectonic mechanisms similar to those that create modern island arcs throughout much of the earth's history, a conclusion that is still controversial (see box). If crustal plates did exist in the Precambrian era, 600 million years ago and earlier, they were apparently much smaller but possibly more numerous; the greenstone belts tend to be hundreds of kilometers in length, not thousands of kilometers like modern island arcs. In any case, the similarities and differences between old and young ore types may be important for exploration—rocks, presumably ancient, that underlie the upper portions of the continents are largely unexplored.

A final class of mineral deposits, whose tectonic derivation is much more speculative, are those ores thought to be formed within a crustal plate, rather than at its boundary. Here the proposed mechanism is penetration of mantle material up through the crust to form a hot spot, possibly as a result of the mantle plumes which have been hypothesized as a driving force for the motion of the crustal plates Hot spots, investigators are suggesting, may have heated the crustal rock, mobilizing metals from sedimentary or crustal materials and concentrating and depositing them nearer the surface. Guild, for example, proposes that the rich lead-zinc ores of the Mississippi Valley may have originated in this fashion Similar proposals have been made for lead-zinc deposits in northwest Africa. In some instances, Guild believes, the minerals themselves have come from the mantle, propelled up through the crust by the heat of the plume Diamonds, niobium, and some rare-earth deposits, for example, are associated with the explosive eruption of mantle materials to the surface and may be attributable to a plume mechanism. Heat from the mantle, perhaps rising near subduction zones, may also provide the energy to mobilize metals present in lower crustal rocks and concentrate them into ore deposits in some circumstances. This mechanism has been proposed to explain the eastward shift from dominantly copper to dominantly lead-silver ores in western North America, and the repeated emplacement of tin ores in only a few areas of the earth.

Newfoundland Mineral Deposits

A striking illustration of the new models of mineral formation is their application to Newfoundland by David F. Strong and his colleagues of the Memorial University, St. John's. Before the opening of the Atlantic Ocean and the separation of North America from Eurasia about 200 million years ago, according to plate tectonic theory, the Appalachian mountains of eastern North America and the Caledonian range in Britain and Norway formed a continuous mountain belt. Although the details of how this ancient mountain range was formed are still a matter of debate, the basic process is thought to have been the opening and eventually the closing of a predecessor or "proto Atlantic" Ocean between about 600 and 450 million years ago. Since Newfoundland sits astride the Appalachian-Caledonian range, it is in many ways an ideal laboratory for exploring how a tectonic cycle that involved the formation and then destruction of large amounts of oceanic crust affected the formation of metallic ores.

The Newfoundland investigators find that most mineral deposits on the island can be classified in terms of specific plate tectonic origins. They include Troodos-type ores in ophiolitic rock assemblages, Kuroko-type ores in volcanic rocks typical of island arcs, porphyry copper deposits in igneous rocks, and Mississippi Valley–type lead-zinc ores.

The geology of Newfoundland is complex and the ore deposits are distributed in both age and location The eastern and western parts of the island are composed primarily of ancient Precambrian rock (older than 600 million years), while the center part of the island is of more recent origin, formed during the proto-Atlantic event and sandwiched in between the older crust as the ocean basin disappeared. Along the western margins of the island are limestones and dolomites, some of which contain Mississippi Valley–type lead-zinc ores These rocks were apparently deposited in shallow waters during the early part of the proto-Atlantic era. Also on the western shores are ophiolites with Troodos-type ores, representing blocks of oceanic crust thrust up onto the limestones and Precambrian rocks. Belts of ore-bearing ophiolites are also found in the central section of Newfoundland, as are volcanic rocks that contain Kuroko-type polymetallic ores. In the eastern part of the island are porphyry ores, apparently emplaced somewhat later in Newfoundland's history as oceanic crust was subducted beneath continental crust in the final closing of the ancient ocean. The pattern, as the investigators see it, is lead-zinc deposits in the west, then copper and iron ores, then overlapping bands of copper, lead, zinc, gold, and silver deposits, and finally occurrences of copper, molybdenum, and tin deposits in the east.

According to Strong, this pattern of mineral deposits with identifiable plate tectonic origins may well be common to the entire Appalachian-Caledonian chain. Limestones bearing lead and zinc are found from Norway to Alabama, always on the westernmost edge of the mountain chains. Also extending along the length of the chain are ophiolites with, in many places, Troodos-type copper and iron sulfides Known occurrences of polymetallic island arc deposits are more scattered, according to Strong, but appear to lie in the central and eastern portions of the Appalachians. Tin occurs in Alabama and Virginia still farther east. The mineral patterns constrain tectonic models for the Appalachians, especially by implying the existence of a southeastward-dipping subduction zone during the formation of the mountain belt, according to Strong. They also have implications for mineral exploration, he believes, since discoveries in Norway could lead to similar finds in Newfoundland and Tennessee or vice versa. Exploration of Newfoundland and eastern Canada has, in fact, accelerated in the past several years.

The new models of ore formation are far from complete and are still some distance from being completely accepted. Still newer ideas concerning the geochemical processes involved and the role of seawater are being proposed, and these will be the subject of a second article But perhaps the most significant aspect of the emerging synthesis between plate tectonic theory and metallogeny is the prospect that, in a resource-hungry world, mineral exploration can increasingly be guided by a detailed understanding of how, and perhaps where, ores are formed and deposited.

—Allen L. Hammond

SECTION IV

USE OF COLOR INFRA-RED IMAGERY IN THE RED RIVER VALLEY, MINNESOTA

Dr. Richard H. Rust
Department of Soil Science
University of Minnesota, St. Paul

Index

IDENTIFICATION AND DELINEATION OF SALINE SOIL AREAS

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During this third year (FY 75) of study of soils in the northern Red River Valley area in Minnesota color infra-red imagery was obtained in early August '74 at approximately the "peak of green" condition in the small grains (wheat, barley, oats). Approximately 75 percent of fields along the study transects (see IARSL Research Report 74-2) were planted, mostly to small grains, although some acreage was planted to sugar beets, potatoes, and alfalfa. This was a higher percentage planted to small grains than in either '72 or '73 and was likely related to higher grain prices and changing government programs.

The coverage of three years' photography and, more particularly, the past two years, was sufficient to provide imagery of a <u>growing crop</u> on nearly all areas along the transect. Since the bare ground imagery provided very little identification of a saline soil condition as compared to the green crop, it was necessary to acquire a minimum of two years' imagery to interpret most of the studied landscape, Figs. 1A and 1B.

On fourteen selected areas along the Clow and Davis transects (see IARSL Research Report 74-2) the color infra-red imagery was density-sliced at the same scale, or larger, to provide reference imagery for ground truth observations on the affected crops, Figs. 2A and 2B. Field conservationists were asked to identify and verify extent of saline effect. Soil samples were taken in areas of good, poor and no wheat growth and conductivity values determined, Table 1.

The purpose of determining Na, Cl, and SO_4 ions was to ascertain the constituents contributing to salinity. Sodium and Cl ions increase by factors of 2 to 4 in extremely saline areas.

As a result of field observations, air photo interpretations, and laboratory data taken in the course of the detailed soil survey of Kittson County over a period of four years (1971-1974), the areas of saline-affected soils are delineated (Fig. 3). This information will be included as a part of the county soil report (National Cooperative Soil Survey, scheduled publication, 1977).

The delineated saline areas are defined as those areas that show the effect of a saline condition on the growing crop, or are observed in the soil itself. The occurrence <u>within the delineated area</u> is so complex that, at this scale, it is not possible to separate the normal soils from the saline. However, it is concluded, on the basis of air photo interpretation of the transect studies, that about 60 percent of the soils <u>within the delineated area</u> are saline-affected.

A further conclusion is that, to use color infra-red imagery for detection of saline soil areas in other agricultural areas of the Red River Valley, would require at least two successive years' of photography to provide small grain signature of any soil area.

Table 1. Chemical tests made on some Kittson County soils in areas of varying quality of wheat growth. (1972-1974).

Soils and Locations	Soil depth (inches)	Conductivity mmhos.	pH	Carbonate %	Na me/l	Cl ppm	SO_4 ppm
Good Wheat Growth[1]							
Northcote	0-6	4.0	7.1	4	8	570	54
4.5 miles	6-12	5.8	7.5	4	22	820	113
SE of	12-24	13.4	7.5	14	49	1320	540
Kennedy	24-36	14.0	7.7	10	53	2220	698
Augsburg	0-8	3.2	8.0	N.D.*	N.D.	N.D.	N.D.
Sec. 7	8-11	4.9	8.3				
T.159N R 47 W	11-18	6.5	8.4				
	18-33	8.1	8.4				
	33-62	8.1	7.9				
Northcote	0-6	4.2	7.4	N.D.	N.D.	N.D.	N.D.
Sec. 29	6-12	10+	7.7				
T.159N R 48W							
Poor Wheat Growth[2]							
Northcote	0-6	10+	7.1	5	66	3960	383
4.5 miles	6-12	10+	7.2	6	65	3960	270
SE of	12-24	10+	7.6	11	65	3000	675
Kennedy	24-36	10+	7.5	14	62	2760	216
No Wheat Growth							
Saline Hegne	0-7	10+	7.4			3028	
Sec. 8	7-9	10+	7.7			1372	
T.162N R 49W	9-13	10+	7.8			4773	
Saline Augsburg	0-7	10+	7.6			155	
Sec. 17	7-11	8.0	8.1			3095	
T.159N R 47W	11-16	7.0	8.1			1535	
	16-27	10+	7.9			2947	
Saline Northcote	0-7	10+	7.0			N.D.	
Sec. 29	7-12	10+	7.0			N.D.	
T.159N R 48W	12-18	10+	7.1			N.D.	

1. Good--no apparent diminution of stand or quality of grain.

2. Poor--less than 50 percent stand, premature lodging.

*N.D. - not determined.

Fig. 1A. Color infrared imagery of Section 5, Davis township, Kittson county showing 400 of 640 acres in small grain (August '74). Uneven stand, particularly in Northeast quarter, related to saline condition. Conductivity greater than 10 mmhos/cm in areas of no growth.

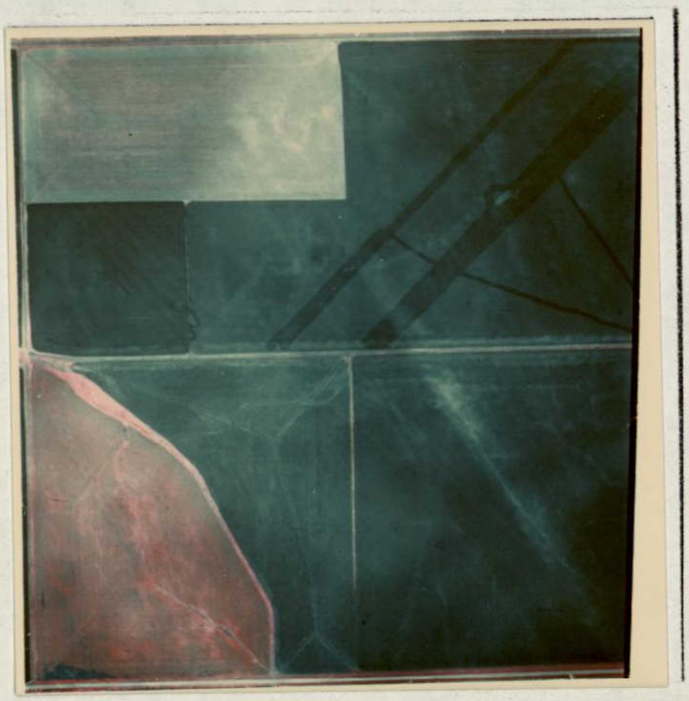


Fig. 1B. Color infrared imagery of same area as in Figure 1A taken in August '73. About 160 of 640 acres was in small grain. Uneven growth in southwest quarter due to severe saline condition. Conductivity greater than 15 mmhos/cm in areas of no growth. Diagonal light area from southeast corner to northwest related to constructed drainageway.

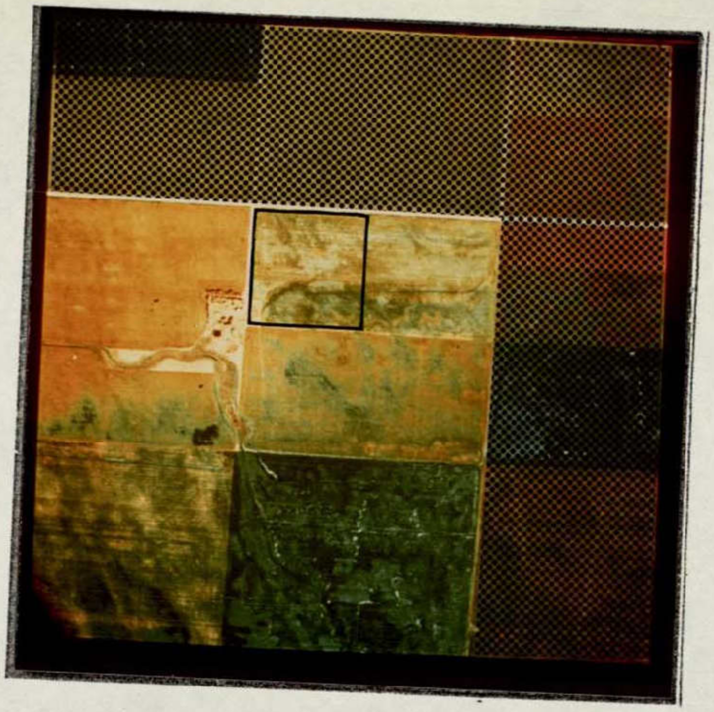


Fig. 2A. Color infrared imagery of Section 9, Davis township, Kittson county (portion along south side of section not included). North half planted to small grain; southwest quarter, planted to mustard; southeast quarter, fallow. Lighter shaded areas in fallow related to greater residue of previous year's small grain. Darker areas relate to lighter (or absence of) residue and indicative of saline condition. August '74.

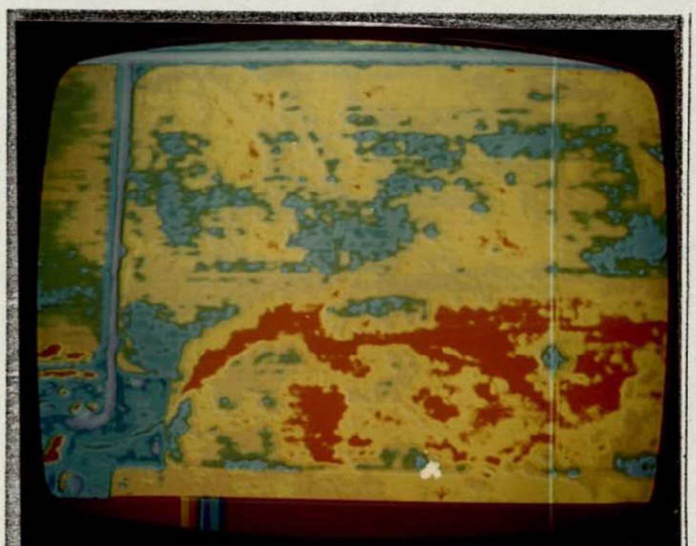


Fig. 2B. Six-level color density slice of northwest quarter of northeast quarter of Section 9 shown in 2A. This 40 acre area planted to barley. Areas of red have no growth; areas of blue and some cyan are of prematuring grain (and poorer quality); areas of yellow and orange are of most nearly normal barley.

SOIL ASSOCIATIONS

MAP OF

KITTSON COUNTY

MINNESOTA

Fig. 3. Soil association map of Kittson county, Minnesota showing occurrence of saline areas as delineated by field observations and air photo interpretation. About 200 of 1124 square miles in the county are included in the saline area, mostly in the western portion and mostly on fine to medium textured soils (Associations 1, 2, 3, 4, 5, and 6, primarily).

LEGEND FOR SOIL ASSOCIATIONS OF KITTSON COUNTY, MINNESOTA

1. Northcote Association: Poorly drained, nearly level clayey soils formed in lake-laid clays.

2. Bearden-Fargo Association: Moderately well-drained to poorly drained, nearly level and gentle sloping soils, formed in lake-laid silts and clays.

3. Hegne-Northcote Association: Poorly drained, nearly level clayey soils with a micro-relief condition.

4. Wheatville-Augsburg Association: Moderately well and poorly drained, nearly level soils formed in very fine sands over clay or deep fine sands.

5. Rockwell-Grimstad Association: Moderately well and poorly drained, nearly level soils formed in fine sands over glacial till.

6. Arveson-Ulen Association: Nearly level, poorly and moderately well-drained calcareous soils formed in fine lake-laid sands.

7. Cormant-Poppleton-Redby Association: Moderately well-drained and poorly drained, nearly level noncalcareous soils formed in deep lake-laid sands.

8. Enstrom-Grygla Association: Moderately well and poorly drained, nearly level noncalcareous soils formed in lake-laid sands over loamy glacial till.

9. Dune Land-Lohnes Association: Excessively to well-drained, nearly level to sloping soils formed in windblown sands or gravelly beach ridges.

10. Percy-Fram Association: Moderately well and poorly drained, nearly level loamy soils formed in glacial till.

11. Mavie-Foxhome Association: Moderately well and poorly drained, nearly level soils formed in loamy material over glacial till with an intervening gravelly layer.

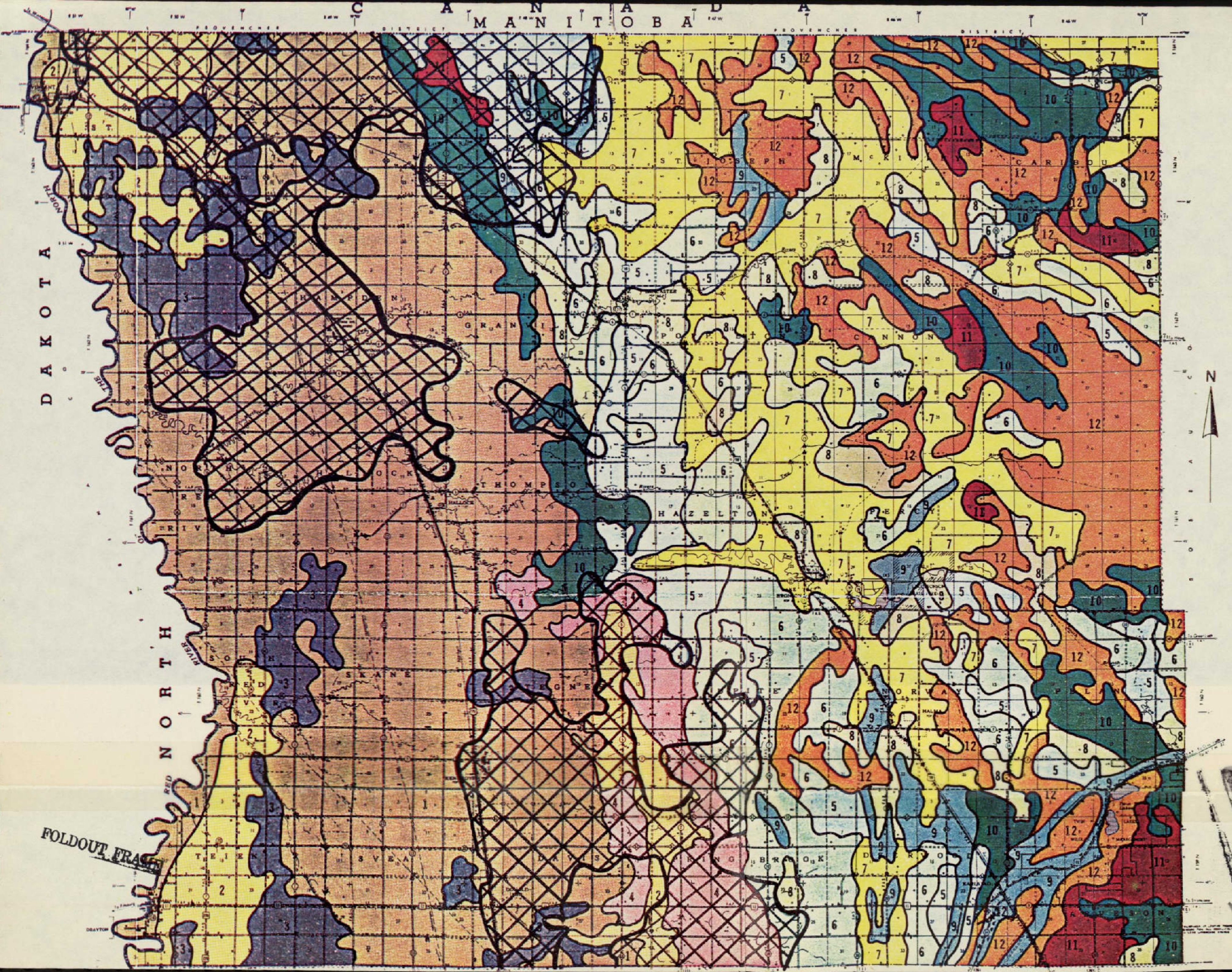
12. Deerwood-Cathro-Markey Association: Nearly level, slightly depressional, very poorly drained soils formed in organic material or organic material over loamy till or sands.

Saline Areas: Refer to saline section for further explanation.

1/200,000 SCALE 1 0 1 2 3 4 5 6 7 8 9 10 Miles

Adapted from map to be published in Kittson County soil report (1977).

C. 3



CANADA
MANITOBA
NORTH DAKOTA
RED RIVER
ST. JOSEPH
CARIBOU
THOMPSON
HAZELTON
PERCY
SKANE
SVEA
NORWAY
N
FOLDOUT FRAME

APPLICATION OF COLOR INFRARED IMAGERY
TO ON-FARM SOIL SURVEYS IN CLAY
COUNTY, MINNESOTA

Investigator: Dr. Richard H. Rust
Department of Soil Science
University of Minnesota, St. Paul

In Clay county (about 100 miles south of Kittson County and mostly in the Glacial Lake Agassiz plain) we obtained (in June '74) color infra-red imagery at a scale of 1:38,000 of some 20 sections along an east-west transect in the area where the field party was initiating the detailed survey. From experience in adjoining Norman County with NASA RB-57 CIR imagery (June '72) Odenyo and Rust (1975) concluded that more accurate delineation of soil landscapes is possible than with the customary panchromatic film.

The field experience in Clay County in July-October '74 suggested that the scale (1:38,000) was not the most appropriate to use in the preparation of 1:20,000 scale maps; also that an earlier date of photography seemed desirable to maximize a bare ground condition.

Accordingly, in May '75 additional CIR imagery in Clay County at a scale of 1:20,000 was obtained in a series of east-west transects in order to cover a maximum variation in soil and plant cover conditions. About 100 mi^2 coverage was obtained. The field scientists will be provided (in July, '75) color transparencies and a portable "skylight" table. They will also be provided black and white internegative prints on which to do field delineations. In this study significant cooperation is being provided by the technical service personnel of the Soil Conservation Service.

A practical application of this effort is primarily the production of more accurate soil maps which form the basis for land use and management recommendations by the county technical people to farm operators. In Clay County, for example, the occurrence of highly calcareous soils poses some real problems in fertilizer recommendations and management for micronutrient response in many crops. Various dollar figures could be assigned to possible benefits or costs depending on the crop, prices, etc. The location of contract sugar beet acreage is also affected.

References

1. Remote Sensing Applications to the Management of Agricultural, Forest, and Water Resources in Minnesota. Chapter 4. Annual Progress Report NASA Grant NGL 24-005-263. 1974.

2. Odenyo, Victor A. and R. H. Rust. Application of Density Slicing Techniques to Soil Survey. Proc. Soil Sci. Soc. of Amer., Vol. 30:311-315. 1975.