C. SYNERGISTIC RELATIONSHIPS AMONG REMOTE-SENSING AND GEOPHYSICAL MEDIA:

GEOLOGICAL AND HYDROLOGICAL APPLICATIONS

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STATUS OF REMOTE SENSING AT THE MINNESOTA GEOLOGICAL SURVEY, 1979

The Minnesota Geological Survey continues to expand the use of remote sensing to understand better and interpret the geology of Minnesota. Space imagery was employed in 1979 to identify and locate bedrock outcrops. A low-level, high-resolution aeromagnetic survey of the state, which began in the fall of 1979, will ultimately provide the best coverage of this sort in the country. Gravity mapping was completed in the St. Cloud and New Ulm sheets at a compilation scale of 1:250,000.

Geochemical methods of remote sensing employed during the past year entailed the measurement of radon in well water in three areas of the state, as well as measurement of gamma radiation taken manually on the ground.

1. Photo Interpretation of Surficial Quaternary Geology

Mapping the Quaternary geology proceeds in various parts of the state. Dr. Saul Aronow mapped the glacial deposits of Dakota County with the assistance of aerial photographs. Dr. Mary Savina used aerial photography to identify and delineate glaciofluvial deposits in Dakota County.

2. Statewide Aeromagnetic Survey

A low-altitude, high-density aeromagnetic survey of the entire state is a major new project for the Minnesota Geological Survey. The current stage involves acquisition of data over Cook, Lake, St. Louis, Carlton and Pine Counties with a 400-meter flight interval at an average terrain clearance of 150 meters. This work is being supervised by Dr. Val Chandler who is interpreting the results as they become available. As will be demonstrated later in this report, aeromagnetic data can be used successfully in combination with other remotely sensed data and traditional geological data sources to make geologic interpretations which none of these sources of data can achieve alone.

3. Radon Survey

In geochemical surveying, given elements may be found to vary in concentration in samples taken systematically over a selected region. When variations in radon activity in ground water are plotted geographically, as contour maps, the resulting image may reveal environmental influences on radon concentration in addition to primary variations in radion emissions from geologic sources. The interpretation of the image depends on consideration of bedrock type and structure, drift thickness, and hydrologic parameters. Richard Lively has demonstrated a relationship between contour maps of radon concentration, kinds of till, and bedrock structure.

4. Ground Survey of Gamma Radiation

A similar imaging technique has been applied to gamma radiation data taken by hand on the ground. This study was initially intended for locating uranium, but the resultant contour map of gamma radiation intensity shows a weak correlation with the distribution of tills and outwash and may separate some till units.

PRESENT STUDY -- SYNERGISTIC RELATIONSHIPS BETWEEN REMOTE-SENSING MEDIA IN IDENTIFYING AREAS OF NEAR-SURFACE BEDROCK

1. Introduction

Although the original intention of this investigation was to locate specific areas in which bedrock is at or very near the surface, bedrock exposures vary too much in character and site, and most are too small to be identified individually by remote sensing. The best example of the problem is the extensive exposures along the Mississippi River which were an important part of this study. Although this bedrock is well exposed in vertical sections, it is covered with about 100 feet of glacial drift behind the river cut. Because all of the media collect data vertically, the outcrop itself is less than the resolution of most remote-sensing media. This investigation therefore reports the identification of areas where bedrock is near the surface and outcrops are likely to occur.

Synergism, as understood here, is the combination of two or more data sources to recognize a geologic characteristic which is not identifiable on any single image. This study was directed toward quantitative evaluation of the usefulness of the data sources and toward developing a procedure to use them for locating bedrock outcrop areas, rather than toward systematic mapping of outcrops.

2. Materials

The following sources of geological data were used in this study:

(1) Topographic maps, for elevation control and geomorphic information.

(2) The aeromagnetic map of Minnesota, at scale 1:1,000,000 as published by the U.S. Geological Survey.

(3) The Bouguer gravity map of Minnesota. Although the primary gravity anomaly sources are within the Precambrian bedrock, the gravity field may locally reflect changes in thickness of the surficial deposits.

(4) Skylab photographs. It was expected that the broad coverage would reveal local changes related to near-surface bedrock that would be more difficult to ascertain on aerial photographs. Also the Skylab photos were made with different filters which might enhance moisture content variations or other factors in areas of thin surficial cover. Skylab coverage included photographs in visual color, color infrared, visual black and white in the red and green range, and black and white infrared in the 0.7-0.8 μm range.

(5) Seven seasons of LANDSAT images, including all four MSS bands for a dry and a wet summer-spring-fall and one winter scene.

(6) Aerial photographs, for information on geomorphology.

(7) A contour map of regional thickness of unconsolidated sediments, supplemented by the Minnesota Geological Survey data base of water-well drillers' logs, was used to reduce the search area to the one-third of the state which has less than 100 feet of glacial drift.

(8) The set of maps of lineaments previously prepared for this study (Goebel and others, 1978). Glacial, fluvial and tectonic processes are responsible for many of the lineaments. We felt that outcrops would occur near these linear features.

(9) A map of glaciofluvial features. Because melt water eroded the soft new glacial drift, outcrops predominantly occur in glaciofluvial deposits.

(10) Side Looking Radar (SLAR) images, reviewed for indications of textural changes of the soils regardless of moisture content.

(11) Blue-line print orthophotos for 7.5-minute topographic quadrangles in Minnesota, at the quadrangle scale. Although the resolution and gray-scale change in density are not very good on these prints, their registration to the topographic sheets permits comparison of patterns on other imagery with topographic features, and allowed us to assure ourselves of feature locations on all remote-sensing media.

(12) Airborne gamma radiation maps. We expected that the outwash should at least be distinguishable from the till because of the differing mineral content in the two sediment types.

(13) The SMS-GOES imagery was considered because it recorded a different spectrum, but we could not locate cloud-free images of Minnesota without browsing through all of the images. No record is kept, that we could find, of cloud-free periods. Imagery from these satellites seems to be considered temporal and is used only for weather observation.

3. Methods

This study was organized to determine which of the remote-sensing media contributed most to the identification and location of areas with shallow bedrock, and to evaluate them quantitatively.

After all of the remote-sensing or imaging media over Minnesota were located and collected, eight sites were chosen which had all of the kinds of image coverage listed above. USGS 7.5-minute topographic maps were used for locating outcrops in the eight sites and for compiling the results of the study.

Four of the eight sites were designated as training sites. The other four sites (referred to hereafter as test sites) were retained to test the procedure developed in the study of the first four sites. All four training sites were first investigated in the field, and bedrock outcrops, near-surface topographic features and stream conditions were plotted on the USGS topographic maps. Two of the training sites had no outcrops, but the Twin Cities and St. Cloud sites had ample outcrops (see site maps in appendix). The rock outcrop locations were then transferred to a 1:250,000 and a 1:1,000,000 scale USGS topographic map to facilitate location of these features on the various remote-sensing imagery.

We then tabulated the responses of each of the remote-sensing media to areas of observed bedrock outcrop (areas where bedrock was within 12 feet of the land surface) to determine which media seemed to distinguish the bedrock areas. Next we determined correlations between media for outcrop areas. This was particularly important in sorting through all of the bands of LANDSAT used in this study.

The Bausch & Lomb Stereo Zoom Transferscope was used to transfer and locate features from different media and different scales onto the same scale. This transferscope also proved useful in transposing two different images onto each other.

We constructed our own densitometer using a sensitive light meter to register multiseasonal LANDSAT imagery to a base map. We did not have, nor could we find, a densitometer which met our specifications. This densitometer is not an exact instrument. Its only function was to select those images which seem to respond consistently in areas of outcrop.

The test sites were field checked after examination of the foregoing media had indicated specific sites to be checked.

We attempted to confirm near-surface (within 10 to 50 feet) bedrock with a portable power drill, but the drill was not successful, especially in saturated sands. Because no other drill was available, we checked the remaining areas to a depth of 20 feet with a hand auger.

4. Results

Near-surface bedrock areas as identified in this study were areas covered with less than 100 feet of glacial drift. Areas where the bedrock is less than 12 feet below the surface are defined for this study as outcrops. When appropriate remote-sensing data were used, bedrock was located about half of the time predicted.

The synergistic relationships among LANDSAT imagery, Skylab photographs, and aerial photographs were useful for establishing a as of near-surface bedrock. Lineaments were located on LANDSAT imagery and aerial photographs during 1978, and near-surface water tables will be located during 1980. Both of these subjects can be identified by remote-sensing methods more reliably than individual outcrops, which are small and occur in a wide variety of environments with a wide range of responses. Bedrock outcrops themselves could not be resolved by any of the data sources used, nor did any combination of data sources specifically identify rock at the ground surface. The data sources could not simply be combined mathemetically to produce a visual image of probable areas of near-surface bedrock. Outcrops and near-surface bedrock had to be verified visually at the site. Despite these drawbacks, the study resulted in a procedure for locating areas of near-surface bedrock within which actual surface outcrops may occur.

Field Criteria Indicative of Near-surface Bedrock

1. Surface rock rubble on the shoulder of hills can cover either bedrock or till.

2. Bluffs, especially along major streams, are often the result of a bedrock resistant to erosion.

3. Trees are somewhat shorter and sparser, but surprisingly stouter, in areas of near-surface bedrock, and they appear darker on photographs. Juniper was observed in some areas where bedrock is less than 40 feet deep, but we made no attempt to validate this observation statistically.

4. Constrictions in the width of floodplains and steepened stream gradients may be caused by near-surface bedrock.

5. Swamps at elevations well above local streams or the regional water table may indicate bedrock control of the flow of the ground water. Constriction at swamp outlets and broad backwater flats indicate possible bedrock influence on surficial morphology.

Sequence of Image Examination

Anomalies specifically related to areas of near-surface bedrock could not be identified in any of the data sources. A stepwise method of restricting the evidence of one source by the evidence of the next source was the most useful procedure for determining outcrop areas. The following procedure evolved in this study:

Step One: A map of the regional thickness of the unconsolidated surficial sediments was used to reduce the search area to the one-third of the state which is known to have less than 100 feet of cover.

Step Two: Broad regional imagery, such as Skylab photographs or leaf-off, early spring LANDSAT images, multispectral bands 4, 5 and 6 was studied to further distinguish candidate sites for near surface bedrock.

Step Three: Potential outcrop areas identified from step two were examined on the aeromagnetic map. We noted a correlation between spectrally-identified areas of potential outcrop and aeromagnetic anomaly levels (relative to arbitrary datum) of 11,000 to 11,500 gammas, but this relationship requires further study.

Step Four: Some statistical correspondence between gravity values within the range of -30 to + 35 milligals and bedrock outcrop areas was observed, but half of the state is within this range. Areas within these limits were considered only if the conditions in the first three stages had been met.

Step Five: After large areas of potential outcrop have been identified, more site-specific methods can be used. Conventional aerial photography is especially useful at this stage. Numerous criteria for outcrop recognition on aerial photographs have been developed over the last 5 years (Cooper, 1978; in press), and these were applied to photographs of the test sites.

Step Six: The areas selected on the basis of the previous steps were located on 7.5-minute topographic maps. Areas less than 50 feet above the elevation of the nearest stream and within 2,500 feet of it were searched for.

Step Seven: The final step was to verify the outcrop on the land.

Comments and Recommendations on Image Types

Of the methods employed in this study, LANDSAT images were analyzed the most thoroughly. We had four MSS bands with seven scenes for each scene center. These seven scenes included a wet and dry spring, a wet and dry summer, a wet and dry fall and a winter image. Of the 28 possible combinations of MSS bands, the bands which had the most uniform intensity of response, as measured on the photographic negatives, and also as deduced from comparing two different scene centers, were:

A dry spring - bands 4, 5 and 6

A wet spring - bands 4 and 5

A dry summer - band 4

Combinations of two or three of the above were best for identifying areas of probable outcrops.

An objective of this study was to establish a method for selecting other bands as possible sources of information about bedrock outcrops. It will require another phase of investigation to acquire these CCT's, develop the training sets, and then predict all of the outcrop areas in each scene.

The areas of shallow bedrock appeared very dark on radar (SLAR) images, as they did on aerial photographs, but because the detail and resolution were better on the aerial photographs we did not pursue the radar imagery as an indication of bedrock outcrop. Skylab photos, visual and infrared, color and black and white, also showed shallow bedrock as very dark or intense colors.

The map of natural gamma radiation intensities, which vary according to surficial conditions, indicated the location of sand, gravel and organic material, but the resolution was not sufficient to identify bedrock near the surface. There was radioactivity coverage over only the study training areas so we could not project this information on the test areas. With better resolution, and with actual flight-line data if they were available, natural gamma radiation data possibly would be a useful indicator of surface or near-surface bedrock.

When aeromagnetic data with higher resolution are available, it will be useful to investigate areas characterized by concurrence of magnetic anomalies and topographic lineaments, and by localized, sharp magnetic anomalies with high gradients and intensity values. This was not practical with the resolution of the available map.

The new, more detailed gravity map now partly completed for Minnesota will be potentially more useful in future studies. The gravity anomaly characteristics at known outcrops for an area would be useful criteria in evaluating gravity data for other areas of possible outcrops.

Relations of Outcrop to Lineaments, Drainage, and Elevation

We looked at lineaments interpreted from many sources (see Goebel and others, 1978) and counted the number of outcrops located within 1 mile and within 2 miles of a lineament. We found that of the lineaments, those interpreted from winter LANDSAT imagery occurred most frequently near outcrops. Although there were many lineaments in the two training areas that had outcrops, there were few in the test areas. Therefore, we could not assess the usefulness of lineaments in predicting outcrops. It would be advisable to review the lineaments in application of this study to other areas.

We tested the hypothesis that bedrock outcrop elevations should be near the base levels of the closest streams, and that they should be fairly close to the nearest stream beds. Topographic maps provided information on elevations above sea level. Two-thirds of the outcrops in the St. Cloud site have elevations less than 50 feet above the elevation of the nearest stream and two-thirds of the outcrops in the Twin Cities site are within 124 feet of nearest-stream elevations.

It was further determined that outcrop is likely to be higher in elevation the farther it occurs from the stream. Most outcrops located were at distances between 1,400 and 5,000 feet from streams, although we found outcrops in streambeds and as far as 8,000 feet away. Except where other evidence is available, it would be useful to concentrate the search in areas less than 50 feet higher than a streambed but no farther than 2,500 feet, or at most 5,000 feet from a stream.

Outcrops occurred dominantly in or very near glaciofluvial and alluvial areas shown on Quaternary Geologic Map of Minnesota. Glaciofluvial excavation of bedrock is consistent with the relationship between stream erosion and outcrops.

CONCLUSIONS

Systematic application of procedures developed in this study can narrow the search area to reasonable limits, and can help define areas where bedrock is near the surface. Some media should be further investigated to understand their contribution to recognizing outcrop areas. More specific attention could be given to quantifying the usefulness and constraints of the recommended procedure for locating bedrock near the surface.

Table 1. Mean and standard deviation of the response values derived for selected remote-sensing media used in this study.

Remote-sensing Medium	Twin Cities		St Cloud	
	M	SD	M	SD
Aeromagnetic map (in gammas mag. rad.)	11,300	246	11,200	180
Bouguer gravity map (in milligals)	3	33	-16	3
Aerial photos (light to dark scale 1-5)	4.5	2.1	4.4	.9
Thickness unconsolidated sediments (ft.)	94	54	53	36
Bedrock outcrop elevation (feet)	852	86	1,072	42
Streambed elevation (feet)	759	29	1,038	35
Distance from outcrop to streambed (ft.)	5,180	7,800	1,421	1,484
SLAR radar (light to dark scale 1-5)	4.7	.5	4.6	.6
Natural gamma radiation (counts/second)	2.9	32.8	-15.7	2.5

	Twin Cities	St. Cloud
Percentage of outcrops occurring in fluvial deposits	79	77

Table 2. Mean and standard deviation for the density values recorded for outcrops in the training sites on LANDSAT Imagery. (Measured on photographic negatives, low numbers are greater film densities.)

Site and Season	Band 4		Band 5		Band 6		Band 7	
	M	SD	M	SD	M	SD	M	SD
Winter								
Twin Cities	2.7	1.0	2.1	.8	2.1	.9	3.0	1.4
St. Cloud	.8	.2	.7	.1	.7	.1	.9	.2
Wet Spring								
Twin Cities	3.9	.6	4.5	1.0	4.4	1.4	4.9	1.8
St. Cloud	3.2	.2	3.8	.3	3.1	1.4	3.3	.5
Dry Spring								
Twin Cities	7.0	1.0	5.5	.1	5.1	.8	6.2	1.6
St. Cloud	6.2	.6	5.3	.5	3.6	.5	4.2	.7
Wet Summer								
Twin Cities	7.4	1.3	6.8	1.4	3.5	1.3	3.8	2.0
St. Cloud	6.9	.8	5.7	1.1	2.8	.6	2.8	.6
Dry Summer								
Twin Cities	4.9	.8	4.2	1.0	3.2	1.1	4.3	1.7
St. Cloud	3.4	.4	2.7	.6	1.4	.3	1.6	.6
Wet Fall								
Twin Cities	7.3	1.1	6.8	1.3	5.6	1.2	6.2	2.2
St. Cloud	(NO COVERAGE)							
Dry Fall								
Twin Cities	8.0	1.6	7.4	1.5	6.9	1.5	8.0	1.8
St. Cloud	6.1	.5	4.6	.6	3.8	.6	4.5	.8

Table 3. Lineaments, Twin Cities Site

Number of lineaments per outcrop	0		1		2		3		4		5	
Distance from outcrop to lineament (km)	1-1/2	6	1-1/2	6	1-1/2	6	1-1/2	6	1-1/2	6	1-1/2	6
Rectilinears from the river map	79	27	27	67	4	6						
Rectilinears from the contour map	62	17	24	51	11	19	1	7		3		3
Rectilinears of rivers on winter LANDSAT	69	13	31	77		4		4				
Rectilinears of rivers on Spring LANDSAT	81	74	19	4								
Rectilinears contacts on Winter LANDSAT	74	64	27	36								
Rectilinears tonal contacts on Spring LANDSAT	100	91		9								
Lineaments of tonal stripe on Winter LANDSAT	100	100										
Lineaments of tonal stripes on Spring LANDSAT	100	100										
Lineaments from the lakes map	87	67	13	29								
Lineaments of lakes on Winter LANDSAT	87	56	13	27		26				6		
Lineaments of lakes on Spring LANDSAT	96	60	4	40		10		10				
Curvilinear from the river map	73	57	24	37	4	14		4				
Curvilinear from the contour map	74	36	19	26	7	33		7				
Curvilinear of rivers on Winter LANDSAT	77	61	16	24	7	14						
Curvilinear of rivers on Spring LANDSAT	71	61	24	30	1		3	9				
Curvilinear of tonal contacts on Winter LANDSAT	81	66	19	24		9						
Curvilinear of tonal contacts of Spring LANDSAT	100	94		6								

These results are the percentage of all of the outcrops occuring within the indicated distance to the assigned number of nearby lineaments. (For maps of lineaments see Goebel, and others, 1978)

Table 4. Lineaments, St. Cloud Site

Number of lineaments per outcrop	0		1		2		3		4		5	
Distance from outcrop to lineament (km)	1-1/2	6	1-1/2	6	1-1/2	6	1-1/2	6	1-1/2	6	1-1/2	6
Rectilinears from the river map	97	90	3	10								
Rectilinears from the contour map	100	100										
Rectilinears of rivers on winter LANDSAT	87	0	10	70	3	26		3				
Rectilinears of rivers on Spring LANDSAT	93	63	6	36								
Rectilinears contacts on Winter LANDSAT	97	37	3	63								
Rectilinears tonal contants on Spring LANDSAT	0	60		33		6						
Lineaments of tonal stripe on Winter LANDSAT	100	87		13								
Lineaments of tonal stripes on Spring LANDSAT	100	100										
Lineaments from the lakes map	97	97	3	3								
Lineaments of lakes on Winter LANDSAT	100	100										
Lineaments of lakes on Spring LANDSAT	100	97		3								
Curvilinear from the river map	87	6	13	83	3	10						
Curvilinear from the contour map	100	93		6								
Curvilinear of rivers on Winter LANDSAT	90	0	6	46	3	53						
Curvilinear of rivers on Spring LANDSAT	90	0	10	65		36						
Curvilinear of tonal contacts on Winter LANDSAT	97	17	10	63		3						
Curvilinear of tonal contacts of Spring LANDSAT	90	6	10	10		66						

These results are the percentage of all of the outcrops occuring within the indicated distance to the assigned number of nearby lineaments. (For maps of lineaments see Goebel, and others, 1978)

Table 5. Mean and standard deviation of the color density values on Skylab photographs with a scale of 1-5 from light to dark. The Twin Cities site was not included on any of the Skylab photographs and these data apply to the St. Cloud site only.

Type of photography	M	SD
Infra-red, color	4.3	1.3
Infra-red, black and white (.7 - .8 um)	4.9	.7
Infra-red, black and white (.8 - .9 um)	4.5	.8
Visible, color	4.1	.9
Visible, black and white (.6 - .7um)	1.7	.8
Visible, black and white (.5 - .6 um)	3.8	.7

Table 6. Correlation between the responses of the remote-sensing media used in this study to near surface bedrock.

Site	Remote-sensing media	Pearson's r
St. Cloud	Gravity vs. aeromagnetics	-.14
Twin Cities	Gravity vs. aeromagnetics	-.01
St. Cloud	Aeromagnetics vs. natural gamma radiation	.00
Twin Cities	Aeromagnetics vs. natural gamma radiation	.14
St. Cloud	Gravity vs. natural gamma radiation	.34
Twin Cities	Gravity vs. natural gamma radiation	-.29
St. Cloud	Aerial photograph vs. radar imagery	-.12
Twin Cities	Aerial photograph vs. radar imagery	.30
St. Cloud	Radar imagery vs. visible color	-.21
St. Cloud	Outcrop elevation vs. stream bed elevation	.83
Twin Cities	Outcrop elevation vs. stream bed elevation	.62
St. Cloud	Outcrop elevation vs. distance to elevation	.29
Twin Cities	Outcrop elevation vs. distance to elevation	.32
St. Cloud	Outcrop elevation vs. sediment thickness	-.57
Twin Cities	Outcrop elevation vs. sediment thickness	-.29
	Skylab Photography (Twin Cities without coverage)	
St. Cloud	Visible color vs. I.R. color	.15
St. Cloud	I.R. color vs. black and white .6-.7 um	-.09
St. Cloud	Black and white .6-.7 um vs. black and white .5-.6 um	.11
St. Cloud	Black and white .5-.6 um vs. black and white .8-.9um	.00
St. Cloud	Black and white .8-.9 um vs. black and white .7-.8 um	.41
St. Cloud	Visible color vs. black and white .8-.9 um	.07
	LANDSAT Image negatives	
St. Cloud	Wet summer band 4 vs. dry summer band 6	.04
St. Cloud	Dry summer band 6 vs. day fall band 4	.53
St. Cloud	Dry spring band 4 vs. dry summer band 6	.62
St. Cloud	Dry spring band 4 vs. dry fall band 4	.72
St. Cloud	Wet summer band 7 vs. dry summer band 6	.91
St. Cloud	Dry spring band 4 vs. wet summer band 7	.66
St. Cloud	Winter band 4 vs. dry spring band 4	.09
St. Cloud	Winter band 6 vs. dry spring band 4	.11

DATA SOURCES

Aerial Photographs

Study Area A - Marshall and Pennington Counties, 1966, U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service, Aerial Survey, Inc., Louisville, KY, 1:20,000.

BXY - 1GG-(65-76), (142-154), (182-189)

BXY - 2GG-(107-114), (161-172), (192-203), (267-278)

BXY - 3GG-(44-48), (68-81), (146-159), (181-194), (264-276)

BXY - 4GG-(79-84), (167-169)

BYC - 1GG-(46-55), (88-97), (163-171)

BYC - 2GG-(56-65), (116-124), (132-141), (206-215)

Study Area B[1] - Lake of the Woods County, 1941, Abrams Aerial Survey Corp. - Mark Hurd Aerial Mapping Corp., 1:20,000.

C1Q-1-(38-145)

C1Q-3-(23-31)

C1Q-5-(119-125), (156-162), (165-171)

Study Area B[2] - Roseau County, 1966, U.S. Dept. of Agriculture, Agricultural Stabilization and Conservation Service, Park Aerial Surveys, 1:20,000.

BYG-2GG-(113-138)

BYG-3GG-(36-48), (50-55)

BYG-4GG-(1-13), (120-132)

Study Area C - Beltrami County, 1939, U.S. Dept. of Agriculture, Agricultural Adjustment Administration, Abrams Aerial Survey Corp. -

Mark Hurd Aerial Mapping Corp., 1:20,000.

CIN-1-(60-77), (83-91), (102-114), (124-133), (140-159)

CIN-2-(36-45), (65-80)

CIN-4-(182-197), (205-217)

CIN-5-(62-83), (122-128)

CIN-6-(4-21), (88-106), (111-116), (124-128)

CIN-7-(33-35)

CIN-10-(79-82)

Study Area D - St. Louis County, 1953, Arrowhead Aerial Surveys, Hibbing, MN.

CIR-1G-(140-156), (163-179), (191-207)

Study Area E - Crow Wing County, 1940, U.S. Department of Agriculture, Agricultural Adjustment Administration, Abrams Aerial Survey Corp. - Mark Hurd Aerial Mapping Corp., 1:20,000.

BXT-1-(55-60), (94-108), (113-128), (161-175)

BXT-4-(106-117), (123-142)

Study Area F - Crow Wing County, 1939, U.S. Dept. of Agriculture, Agricultural Adjustment Administration, Abrams Aerial Survey Corp. - Mark Hurd Aerial Mapping Corp., 1:20,000.

BXT-2-17-(49-59), 72-79), (101-110), (144-154)

BXT-3-(41-52), (95-104), (122-133), (171-181)

BXT-5-(2-15), (27-38), (69-86), (101-113)

Study Area G - Benton, Sherburne, Stearns, and Wright Counties, 1963, U.S. Dept. of Agriculture, Agricultural Stabilization and Conservation

Service, Mark Hurd Aerial Surveys, Inc., 1:20,000.

BIN-1DD-(75-82), (92-93), (142-143)

BIN-2DD-(19-20), (58-63), (100-101), (133-134), (171-172), (228-229) (266-267)

BJL-1DD-(38-39), (84-91), (143-154), (156-176), (181-201), (204-268)

BJL-2DD-(21-39), (40-57), (101-118), (124-132), (210-227), (267-279)

BJL-3DD-(5-11)

Study Area H^1 - Hennepin County, 1951, Mark Hurd Aerial Surveys, Inc. Wide Angle, 1:9,600.

BF-2-(1-8), (76-93)

BF-3-(35-43), (64-70)

BF-6-(60-65)

Study Area H^2 - Hennepin and Ramsey Counties, 1957, U.S. Dept. of Agriculture, Commodity Stabilization Service, Mark Hurd Aerial Surveys, Inc., 1:20,000.

BIM-2T-1

WO-2T-(52-72), (128-135). (201-209)

WO-3T-(2-10)

WO-9T-(65-71)

Study Area H^3 - Dakota and Washington Counties, 1964, U.S. Dept. of Agriculture, Agricultural Stabilization and Conservation Service, Mark Hurd Aerial Surveys, Inc., 1:20,000.

CZ-2EE-(22-38), (107-125)

CZ-3EE-(1-27), (83-107)

CZ-4EE-(53-63), (190-216)

CZ-5EE-(45-62)

LANDSAT IMAGES

EROS Data Center, LANDSAT Imagery, U.S. Dept. of the Interior, Geological Survey, EROS Data Center, Sioux Falls, S.D., 1:1,000,000

Black & White Negatives:

8-2359-16173-4,5,6,7

8-5353-15515-4,5,6,7

8-2197-16201-4,5,6,7

8-2269-16192-4,5,6,7

8-2791-16043-4,5,6,7

8-2593-16121-4,5,6,7

8-2665-16094-4,5,6,7

8-2018-16236-4,5,6,7

8-5354-15571-4-4a,5,6,7

8-2198-16253-4,5,6,7,

8-2828-16075-4,5,6,7

8-2594-16172-4,5,6,7

8-2648-16154-4,5,6,7

SKYLAB Images

EROS Data Center, SKYLAB Images S190A, U.S. Dept. of the Interior, Geological Survey, EROS Data Center, Sioux Falls, S.D., 1:2,822,434.

G30A043216000	Infrared Positive	Black & White Positive
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G30A048217000		BW
G30A045217000	IR	Color
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G30A043218000	IR	BW
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G30A026008000	IR	BW
G30A029008000		BW
G30A030008000		BW
G30A027008000	IR	Color
G30A028008000		Color

SLAR Images

Goodyear Aerospace Corp., Side Looking Airborne Radar Imagery (SLAR): Goodyear Aerospace Corp., Litchfield Park, Arizona, 1:200,000.

RNI	FN	1068X	Poss#03	Pos. Paper and Film
RN3792	FN	129X	Poss#07	Pos. Paper and Film

Orthophotographs

Blue-line orthophotographs, Mark Hurd Aerial Surveys, Inc., 345 Pennsylvania Ave. So., Mpls., MN. 55426, 1:24,000.

Sucker Creek	392-2	1977
Nebish	361-2	1977
Redby N.E.	361-1	1977
Borden Lake	360-2	1977
O'Brien Lookout Tower	360-3	1977

Saum	360-4	1977
Saum N.E.	360-1	1977
Shotley	391-3	1977
Shotley Brook	391-2	1977
South Long Lake	213-2	1977
Merrifield	213-4	1977
Riverton	213-1	1977
Brainerd	213-2	1977
Prescott	103-2	1977
St. Paul Park	103-3	1977
Lake Elmo	104-4	1977
Hudson	103-1	1977
St. Paul West	104-4	1977
St. Paul East	104-1	1977
St. Paul S.W.	104-3	1977
Inver Grove Heights	104-2	1977
Viking S.W	399-3	1969
Viking S.E.	399-2	1969
Warroad S.E.	446-2	1969
Roosevelt	445-2	1969
Winter Road Lake N.W.	434-4	1969
Winter Road Lake	434-1	1969
Milligan Lake N.E.	435-1	1969
Monticello	139-2	1977
Silver Creek	139-3	1977

Clear Lake	139-4	1977
Elk River	138-2	1977
Big Lake	138-3	1977
Orrock	138-4	1977
Lake Fremont	138-1	1977
Becker	139-1	1977
Boulder Lk. Reservoir	269-3	1969
Boulder Lk. Reserv. N.E.	269-1	1969
Comstock Lake	269-4	1969
Thompson Lake	269-2	1969
Arnold	246-1	1969
Fredenberg	246-4	1969
Shaw	270-2	1969
Trommald	233-2	1977
Pelican Lake	233-3	1977
Stewart Lake	254-3	1977
Mitchell Lake	254-2	1977
Roosevelt Lake	253-3	1977
Edna Lake	253-2	1977
Twig	247-1	1969
St. Cloud	158-3	1977
Cable	158-2	1977
St. Augusta	140-4	1977
Clearwater	140-1	1977
Minneapolis North	121-2	1977

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Minneapolis South	105-1	1977
Stillwater	119-2	1977

Maps

Aeromagnetic

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Neuschel, S.K., 1969, Natural Gamma Aeroradioactivity Map of Minneapolis-St. Paul Area, Minnesota-Wisconsin: U.S. Geological Survey, Geophysical Investigations Map GP 658, 1:250,000.

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U.S. Army Map Service (BEAM), Western United States, 1:250,000 Topographic Map Series, U.S. Army Corps of Engineers, Wash., D.C., for sale by U.S. Dept. of the Interior Geological Survey.

Bemidji, Minnesota Sheet, 1954 (Limited Revision 1965)

Brainerd, Minnesota Sheet, 1953 (Limited Revision 1965)

Duluth, Minnesota-Wisconsin Sheet, 1953 (Limited Revision 1963)

Hibbing, Minnesota Sheet, 1954 (Limited Revision 1965)

Roseau, Minnesota, U.S.-Ontario, Can. Sheet, 1954 (Limited Revision 1968)

U.S. Dept. of the Interior Geological Survey, 1965, State of Minnesota (Base Map), U.S Dept. of the Interior Geological Survey, 1:1,000,000.

U.S. Dept. of the Interior Geological Survey, Topographic Quadrangles, U.S. Dept. of the Interior Geological Survey, Wash., D.C.

Arnold MN	7.5'	1953
Becker, MN	7.5'	1961
Big Lake, MN	7.5'	1961
Borden Lake, MN	7.5'	1972
BoulderLk.Reservoir, MN	7.5'	1953 photorevised 1969
BoulderLk.Reservoir N.E.,MN	7.5'	1957
Brainerd, MN	7.5'	1973
Cable, MN	7.5'	1974
Clear Lake, MN	7.5'	1961
Clearwater, MN	7.5'	1974
Comstock Lake, MN	7.5'	1957
Edna Lake, MN	7.5'	1970
Elk River, MN	7.5'	1961
Fredenberg, MN	7.5'	1953 photorevised 1972

Hudson, MN-WI	7.5'	1967 photorevised 1972
Inver Grove Heights, MN	7.5'	1967 photorevised 1972
Lake Elmo, MN	7.5'	1967 photorevised 1972
Lake Freemont, MN	7.5'	1961
Merrifield, MN	7.5'	1973
Minneapolis North, MN	7.5'	1967 photorevised 1972
Minneapolis South, MN	7.5'	1967 photorevised 1972
Mitchell Lake, MN	7.5'	1970
Monticello, MN	7.5'	1961
Mulligan Lake N.E., MN	7.5'	1968
Nebish, MN	7.5'	1972
Newfolden, MN	15 '	1957
O'Brien Lookout Tower, MN	7.5'	1972
Orrock, MN	7.5'	1961
Pelican Lake, MN	7.5'	1959
Prescott, MN	7.5'	1967 photorevised 1972
Redby N.E., MN	7.5'	1972
Riverton, MN	7.5'	1973
Roosevelt, MN	7.5'	1967
Roosevelt Lake, MN	7.5'	1970
Rosewood, MN	7.5'	1959
St. Augusta, MN	7.5'	1974
St. Cloud, MN	7.5'	1974
St. Paul East, MN	7.5'	1967 photorevised 1972
St. Paul Park, MN	7.5'	1967 photorevised 1972

St. Paul S.W., MN	7.5'	1967 photorevised 1972
St. Paul West, MN	7.5'	1967 photorevised 1972
Saum, MN	7.5'	1972
Saum, N.E., MN	7.5	1972
Shaw, MN	7.5'	1953
Shotley, MN	7.5'	1973
Shotley Brook, MN	7.5'	1974
Silver Creek, MN	7.5'	1961
South Long Lake, MN	7.5'	1973
Stewart Lake, MN	7.5'	1971
Stillwater, MN-WI	7.5'	1951 photorevised 1972
Sucker Creek, MN	7.5'	1973
Swift, MN	7.5'	1967
Thompson Lake, MN	7.5'	1954 photorevised 1969
Trommald, MN	7.5'	1959
Twig, MN	7.5'	1953 photorevised 1969 and 1972
Viking, MN	7.5'	1959 photorevised 1976
Viking S.E., MN	7.5'	1959
Viking S.W., MN	7.5'	1959
Warroad S.E., MN	7.5'	1967
Whiteface, MN	7.5'	1956
Winter Road Lake, MN	7.5'	1958
Winter Road Lake N.W., MN	7.5'	1968

Other

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Goebel, J.E., Walton, M., and Batten, L.G., 1978, Synergistic relationship between lineaments located on LANDSAT imagery and traditional sources of topographic information, in A study of Minnesota land and water resources using remote sensing: University of Minnesota Space Science Center, NASA Grant NGL 24-005-263, v. XII, p. C1-C50.

Sims, P.K., and Morey, G.B., eds., 1972, Geology of Minnesota: a centennial volume: Minnesota Geological Survey, 632 p.

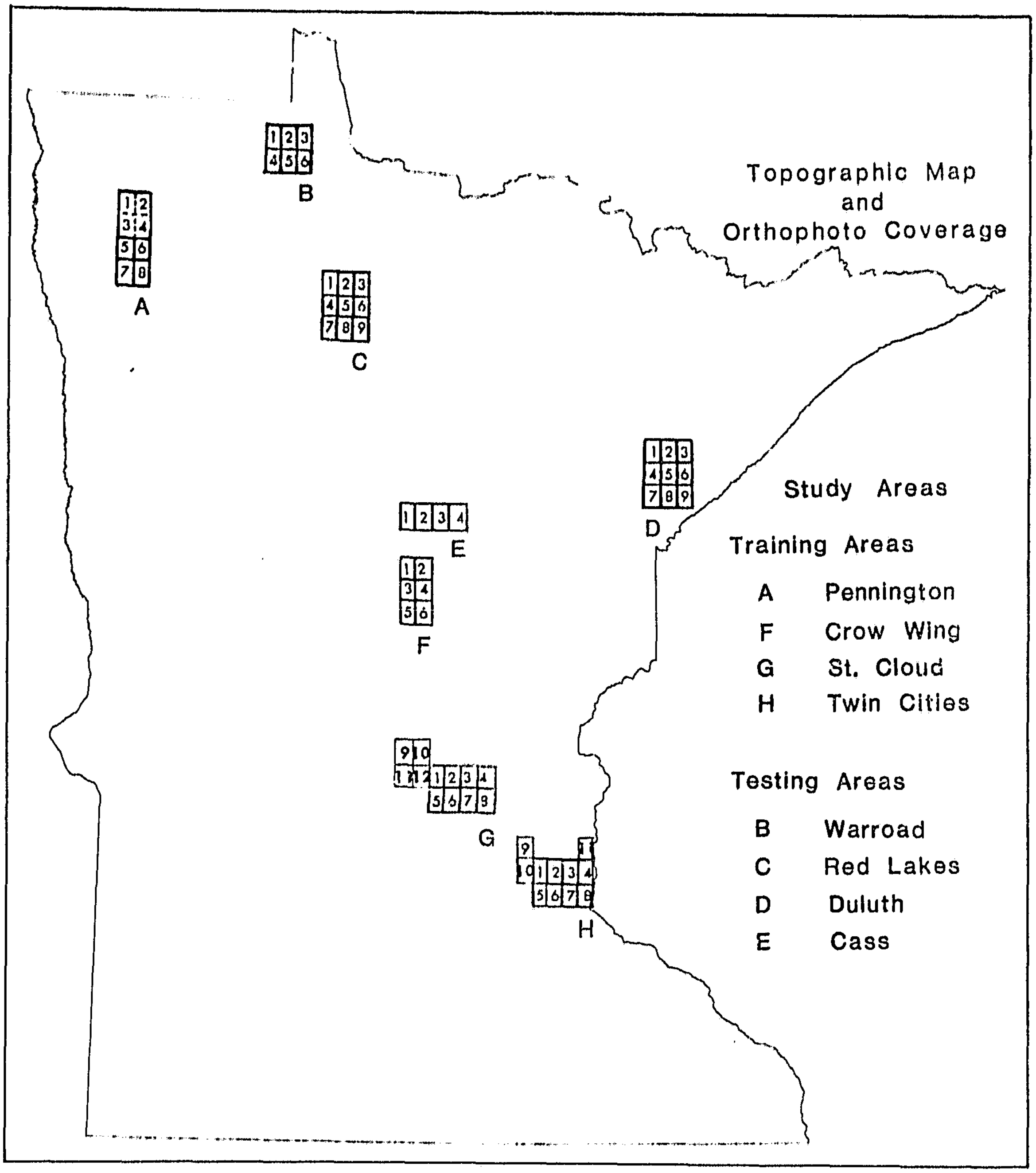

Figure 1. Index map of topographic maps and orthophotos coverage used in this study. For the list of each map or orthophoto see Data Sources.

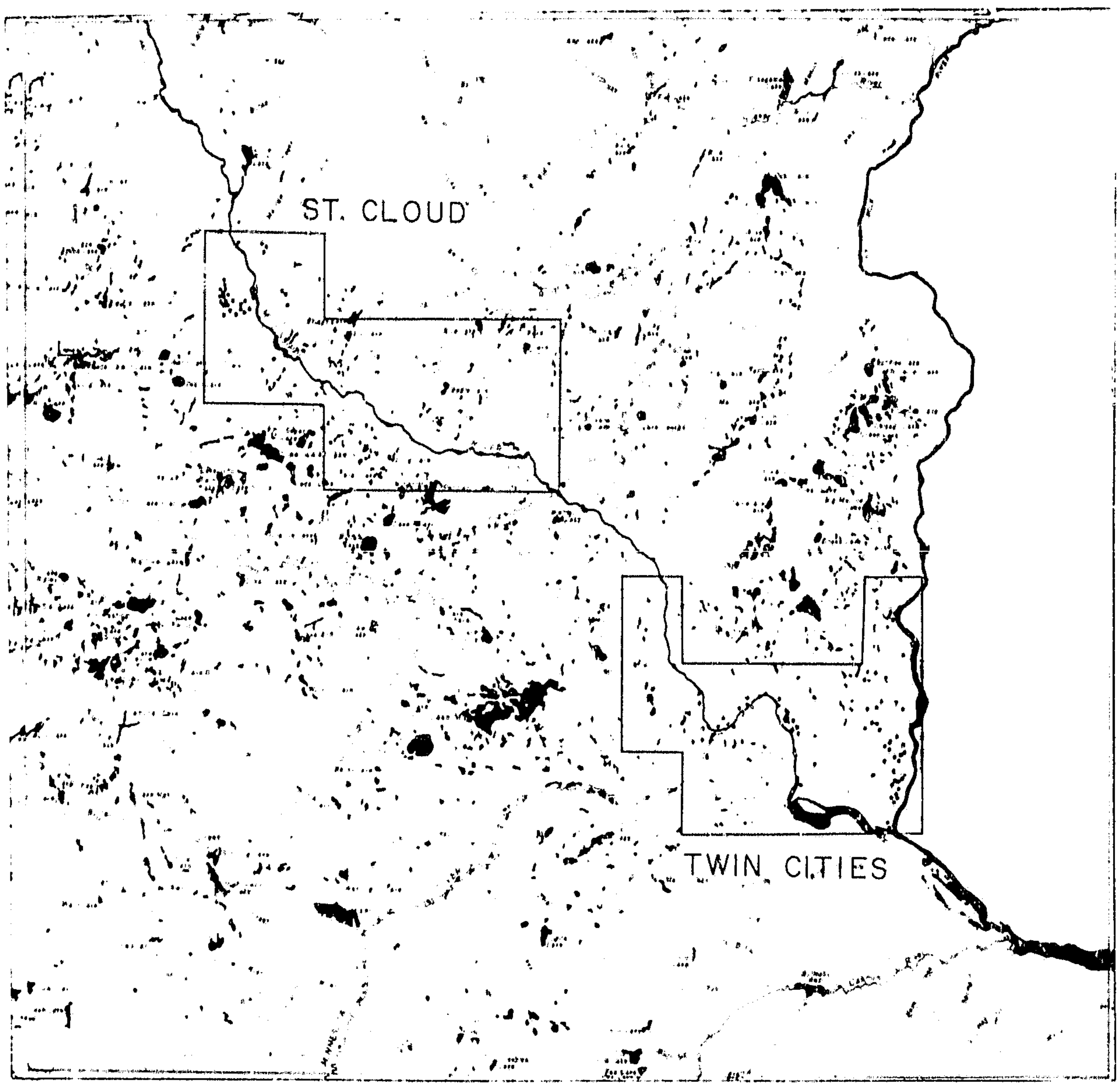

Figure 2. Bedrock outcrops located in the St. Cloud and Twin Cities training sites.

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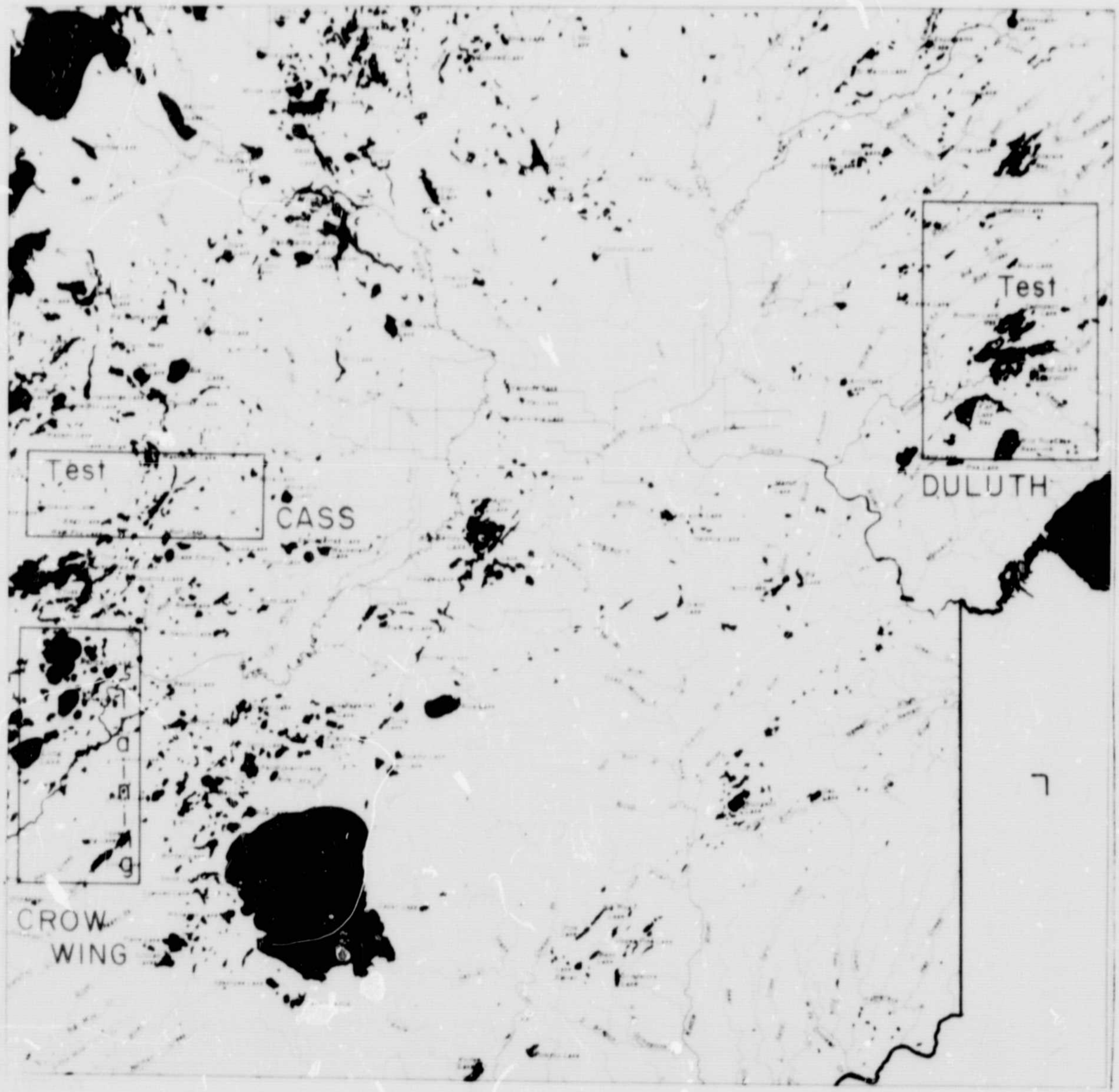

Figure 3. Bedrock outcrops located in the Crow Wing training site and the Cass and Duluth test sites.

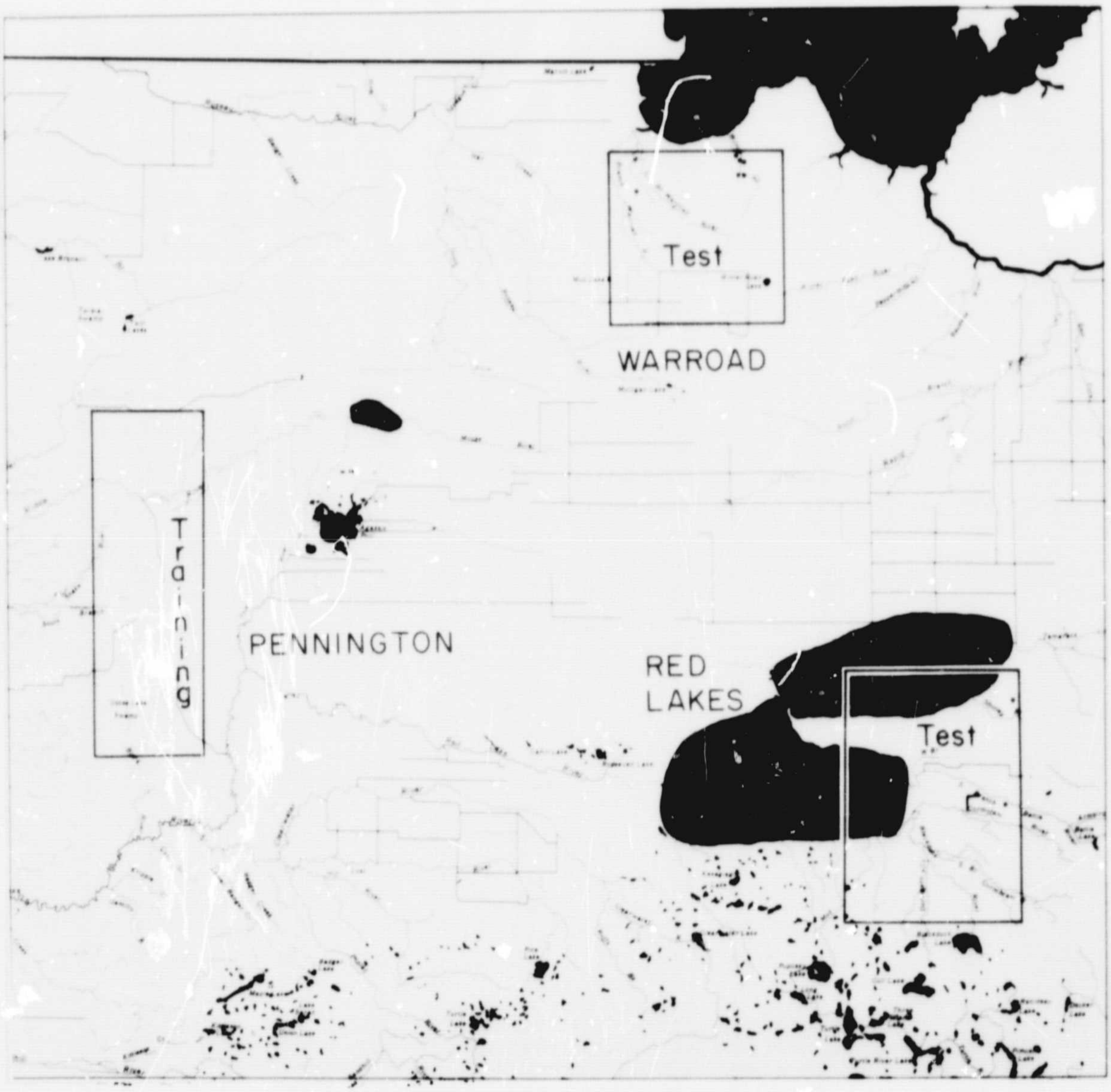

Figure 4. Bedrock outcrops located in the Red Lakes and Warroad test sites. No outcrops were located in the Pennington training site.

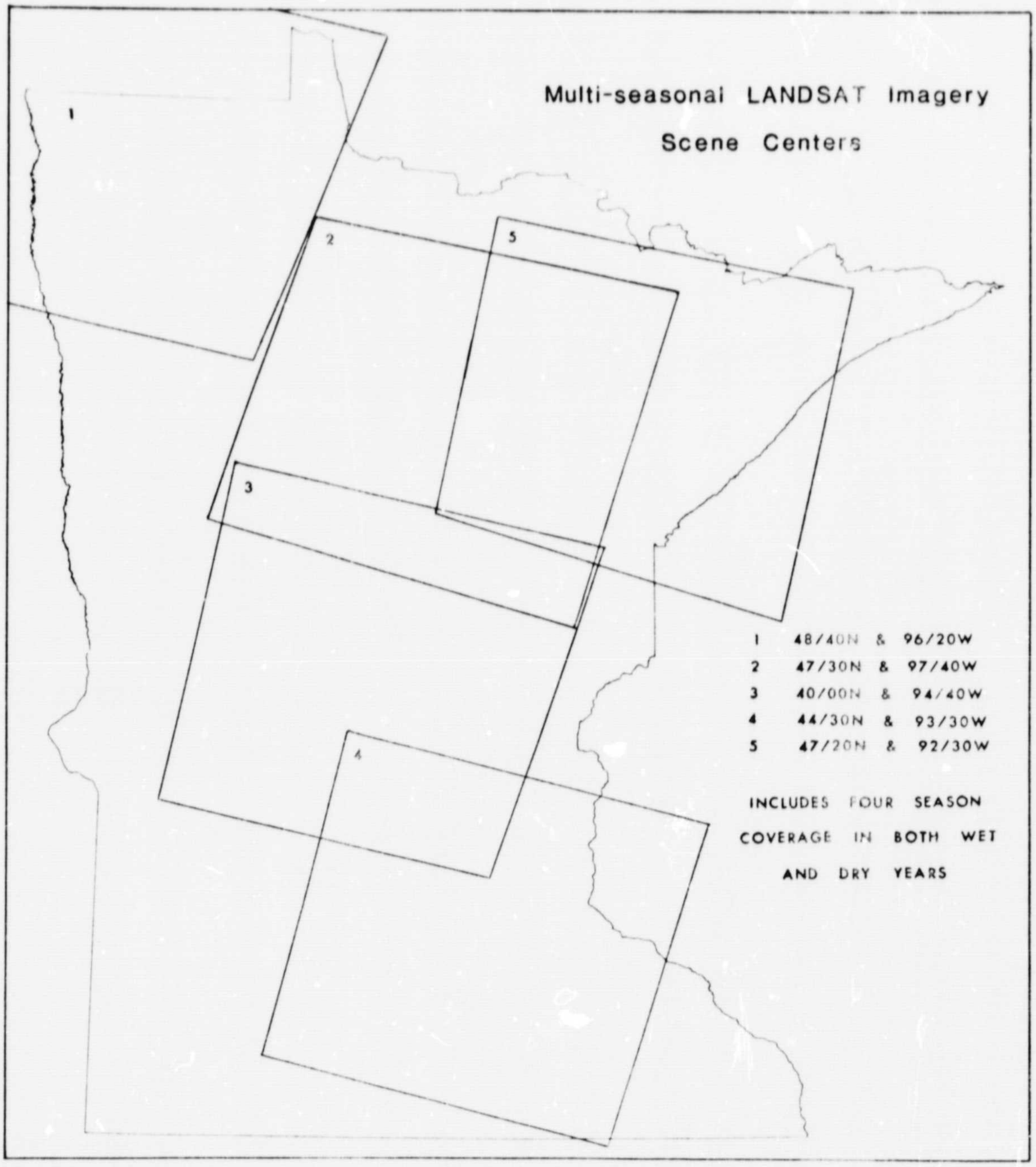

Figure 5. Index map for multiseasonal LANDSAT MSS imagery scene centers. Each scene center has imagery related to a wet and dry year for spring, summer and fall while winter has single coverage. For the list of all of the images used in this study, see Data Sources.

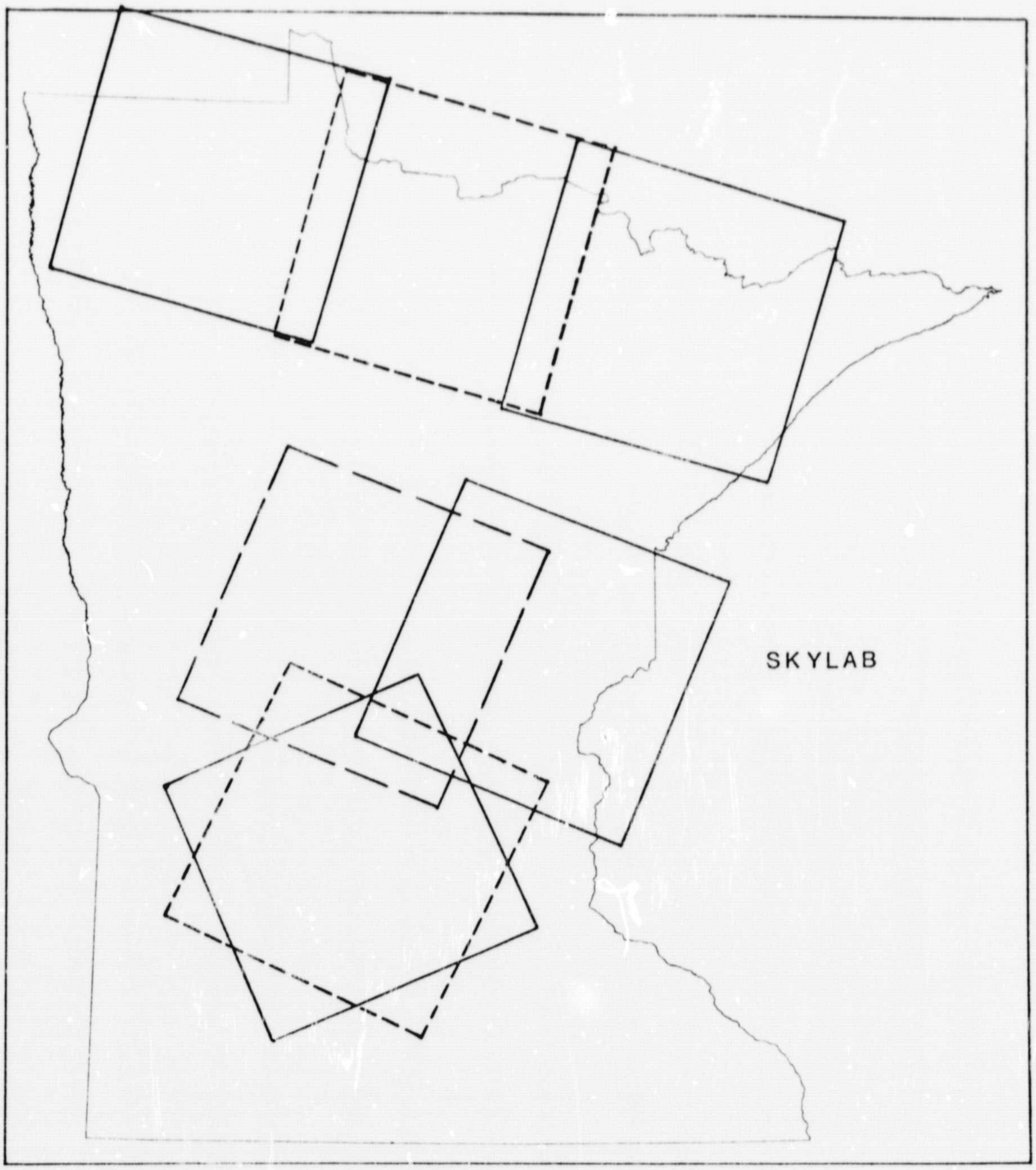

Figure 6. Index Map of Skylab photographs.

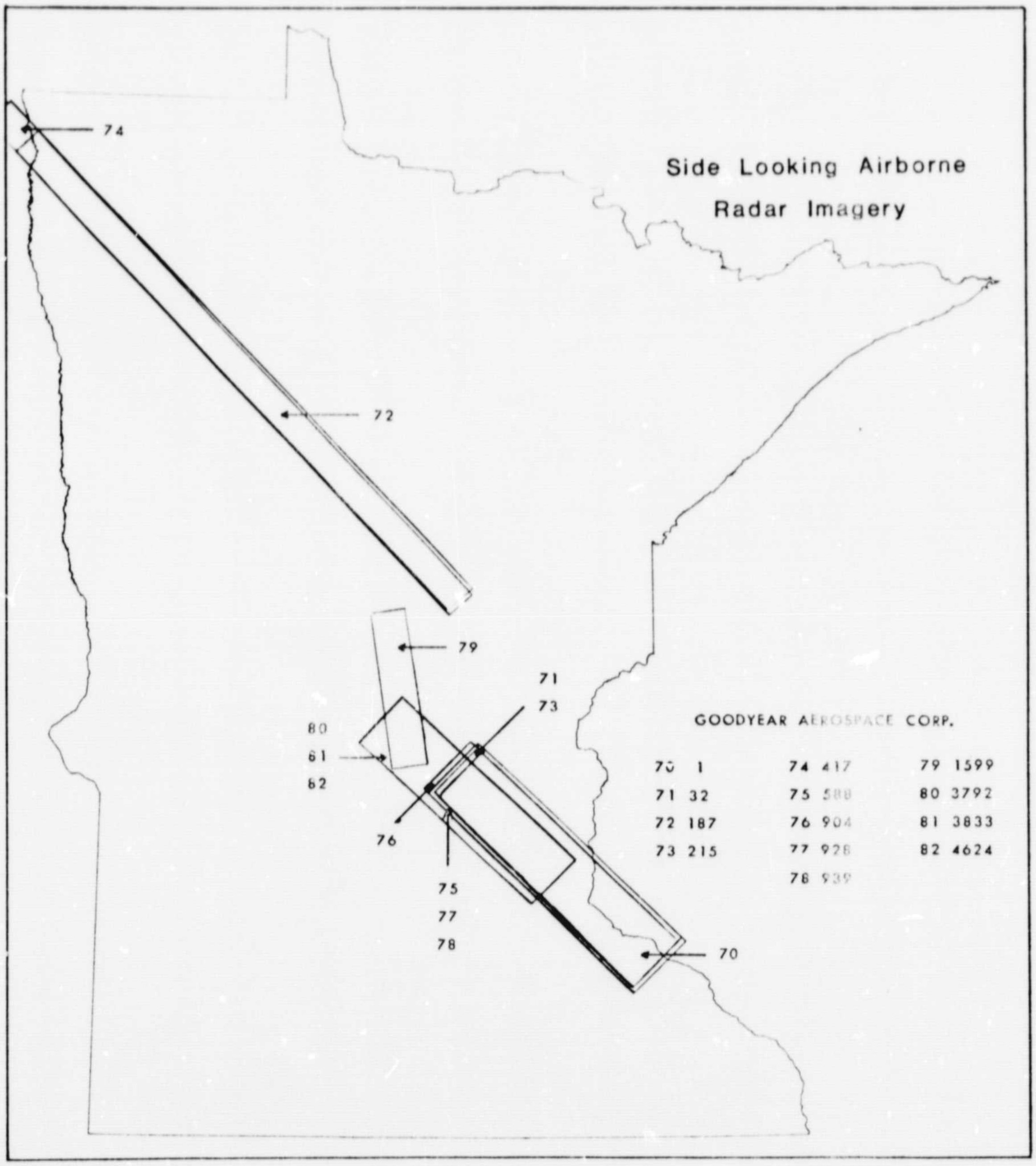

Figure 7. Index map of SLAR imagery.

Figure 8. Reduced aeromagnetic map of Minnesota.

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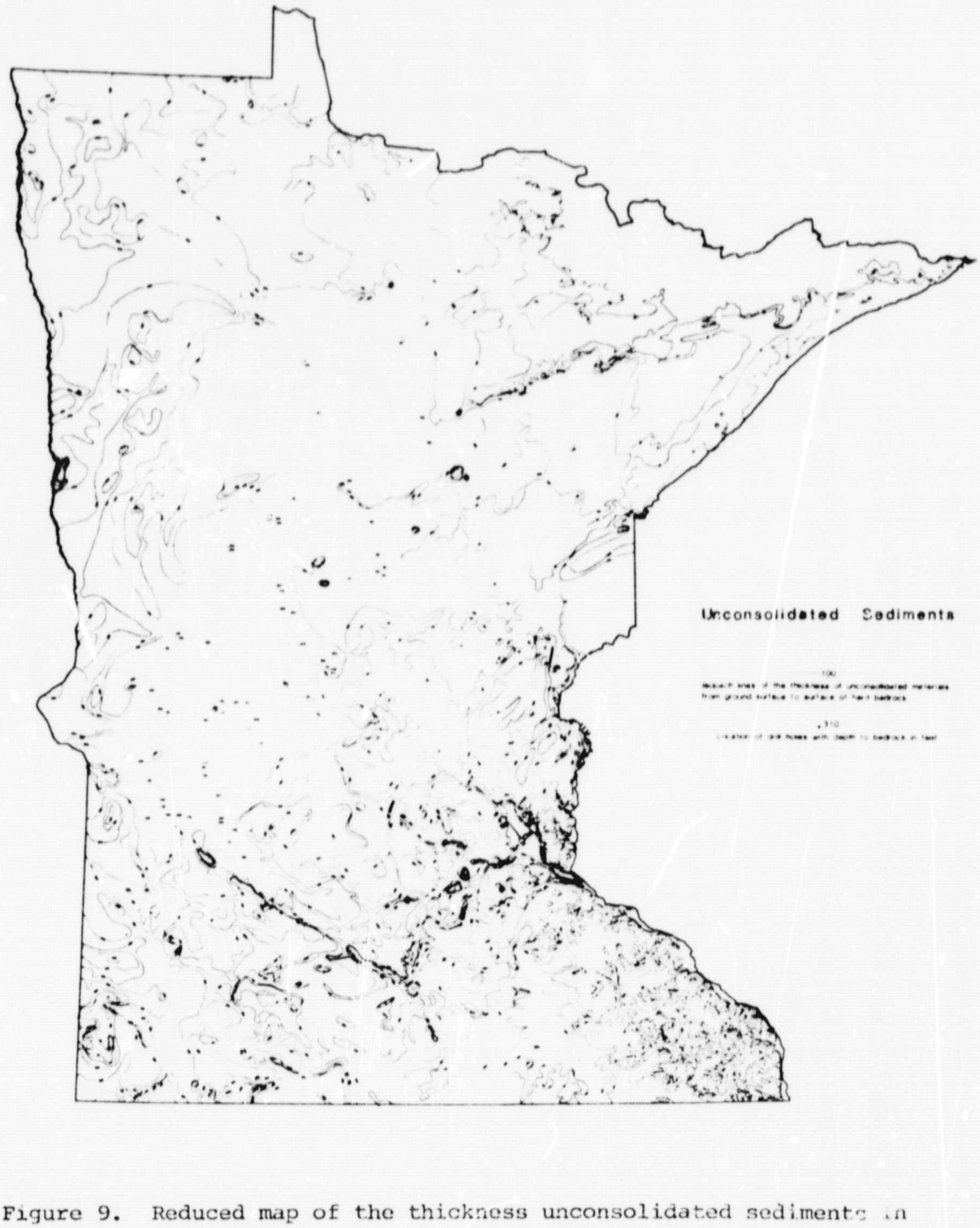

Figure 9. Reduced map of the thickness unconsolidated sediments in Minnesota.

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Figure 10. Reduced map of areas where the bedrock is exposed or thinly covered with unconsolidated deposits.

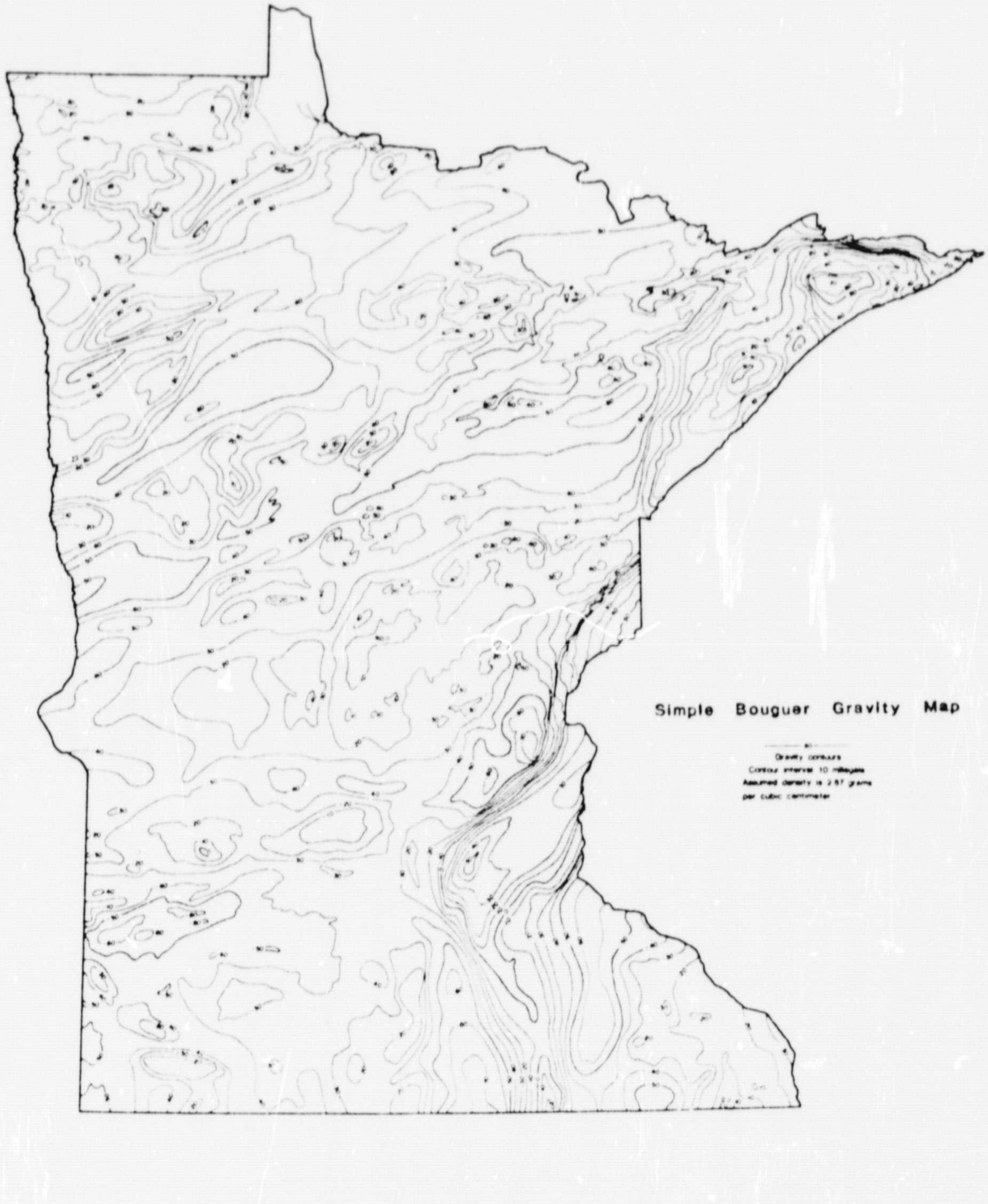

Figure 11. Reduced simple Bouguer gravity map of Minnesota.

N81-12509

SECTION D

A PROJECT TO EVALUATE MOISTURE STRESS IN CORN AND SOYBEAN AREAS OF WESTERN AND SOUTHWESTERN MINNESOTA

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