DEPARTMENT OF NATURAL RESOURCES

Historical Airborne-Geophysical Surveys on file at Minnesota DNR

June, 2021

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Expanded Title Page

Historical Airborne-Geophysical Surveys on file at Minnesota DNR

Compiled from Mineral Exploration Records and Mineral Potential Project Files

of the

Minnesota Department of Natural Resources

Lands and Minerals Division

Hibbing, Minnesota

Mineral Potential Project No. 407

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Summary

Airborne geophysical surveys are used to record magnetic, conductive, and occasionally radiometric or density properties of earth materials. They are deployed most often at early stages of geological investigation so that geologists and geophysicists can make reconnaissance-level interpretations of the grain and character of concealed bedrock sources, and identify field anomalies that may be associated with mineral deposits. This report describes activities directed at discovering, organizing and indexing historical (hardcopy) airborne geophysical surveys on file at the Minnesota Department of Natural Resources (MnDNR).

One-hundred and thirty-three nongovernment public domain hardcopy airborne geophysical surveys have been found on file, recorded on 759 large format maps, accompanied by contractor reports, flight line profiles, and other contractor deliverables. The surveys, most of which are combined aeromagnetic-electromagnetic surveys, cover 179,476 line-kilometers of acquired data (as digitized), on 9,080 flight lines. These survey materials, accounting for about 30% of the physical volume of MnDNR exploration archive records, have been rescued, cleaned, organized, inventoried, scanned and georeferenced where appropriate, and packaged for long term storage in suitable archive-quality office boxes and map cabinets. Some evidence has also been found of another 30 historical surveys that are not held in MnDNR files.

The project effort has produced geographic indexes (shapefiles) of survey footprints, flight line traces, and map tiles. As well, a spreadsheet index of inventoried documents has been generated. Inventoried documents have been scanned to PDF/A format, and large-format maps have been additionally saved in TIFF format. Georeferencing links have been generated to accompany the TIFF map images. Based on outcomes of the current project work, a future effort to seek donation of additional surveys into public domain should be considered. It is recommended that project funding be sought for an effort to scan and convert the volumes of hardcopy survey profile data to PDF/A format, for preservation, access and reuse purposes.

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Introduction

Much of Minnesota's bedrock is concealed by deposits of glacially transported materials (tills, outwash sands and gravels, clays) and vegetation, soils, lakes and wetlands. In absence of direct bedrock exposure that can be examined and mapped by geologists, indirect methods have been developed to help "see" or detect the character and geologic framework of buried bedrock.

One of the best methods for seeing buried rocks is to actually retrieve small pieces from beneath the concealing cover, through use of a drill to obtain chips or core samples. But drill sampling as a mapping technique is very expensive. It is common, therefore, to utilize other lower-cost indirect methods to map the grain and character of unseen bedrock, as a means to better target the deployment of the more expensive sampling and mapping methods.

Among these less-costly indirect methods are airborne geophysical surveys, which are used to record magnetic, conductive, and occasionally radiometric or density field properties associated with bedrock, over areas larger than can be surveyed efficiently by ground-based work. Geophysical field properties of bedrock can often be detected and mapped some distance away from the concealed source, allowing geophysicists and geologists to make reconnaissance level interpretations of the source rock at small cost per unit area.

Project activities described in this report have been directed at discovering, organizing and reporting on historical hardcopy airborne geophysical surveys that have been found at the Minnesota Department of Natural Resources (MnDNR), so that knowledge of, access to, and curation of these fundamental geoscience data are enhanced for mapping, research and land management activities.

Project Basis

Mineral exploration and scientific research data in the collections at the MnDNR Lands and Minerals Division facility in Hibbing include a large volume of unpublished hardcopy airborne geophysical survey deliverables from industry surveys, including maps, flight line profiles, flight records, interpretation reports and other materials. Office boxes full of flight line profiles, large rolls of heavy Mylar maps, 35mm film strips, contractor reports and other deliverables are interspersed among site level exploration records, and together occupy some 30% of the physical volume of the archives. These survey materials are public domain assets available for examination and reuse, but there is waning corporate knowledge of the extent and variety of these materials, and limited availability for remote access while in hardcopy format. There is also risk of physical loss of these unique geophysical materials, that can provide insight on previous exploration programs and potentially also inform new geoscience investigations.

From a collections perspective, an opportunity is recognized to curate and handle these surveys in one logistical exercise, due to the similarity of physical deliverables associated with them, and the fact that they are easily separated as stand-alone contractor surveys. Beyond the benefits of consistent handling, cataloging, and more compact overall storage, segregating these airborne surveys allows the remaining volume of exploration collections to be substantially smaller and more easily addressed as subsequent archive updates are implemented.

An opportunity is also recognized to make digital copies of documents where possible, not only to enhance remote access, but also to serve as critical backup to otherwise irreplaceable hardcopy. A project undertaken to better curate the existing holdings can serve as a vehicle to introduce the geography of mineral exploration data collections to newer mineral potential geoscientists, and as a means to build geographic indexes (shapefiles) of available data. These indexes, and wider corporate knowledge of the data resulting from such an effort, will in turn make the materials easier to find and use in support of geologic survey mapping, university and industry research, and natural resources land management work.

Some Background on Airborne Geophysical Surveys and Their Deployment in Minnesota

The nongovernment hardcopy historical airborne geophysical surveys described in this report were first generated as industry follow up to governmental airborne surveys. They yielded higher resolution exploration insights in support of mineral exploration programs at select areas. Hardcopy deliverables from many of these surveys are on file at MnDNR, and can be found in exploration records reaching up into the 1980's. A general understanding of how first- and second-generation governmental airborne survey work relates to industry survey activity can be helpful in understanding the original purpose and use of these nongovernment surveys.

Airborne magnetic survey methods were first developed to hunt for submarines during World War II. Hanna (1987) reports that the U.S. Geological Survey (USGS) at that time was consulted about rock mass effects on Navy magnetometers, and that the potential for application of these methods to geoscience and mineral resource investigations was quickly recognized. Hanna describes that this recognition led to the first regional aeromagnetic survey by USGS and the Navy, in Alaska, in 1945. National security restrictions on the technology were lifted in 1946, making the technique available for civilian use (Hanna, 1987).

The first airborne geophysical survey data in Minnesota were acquired in 1947, when the USGS flew two rounds of aeromagnetic survey in an area west of the Mesabi Iron Range. This survey area included the Cuyuna Iron Range, plus some long linear dipneedle magnetic trends now known as the Leech Lake Structural Discontinuity, and other dipneedle anomalies in Otter Tail and Becker Counties. Henderson and Mueschke (1953) describe the project purpose of these flights being *"to delineate major magnetic trends associated with known deposits and identify areas under the glacial overburden which may be favorable for additional exploration"*. The surveys were designed "*to cover the largest area possible with minimum flying"*, and survey products from these flights were understood to be *"not sufficient to contour accurately the local minor features"*. Flight line traces in the 1947 surveys for the most part followed north-south Public Land Survey section lines having ~1-mile line spacing. This matching of flight lines to readily visible section-line ground features likely contributed significantly to positional control and accurate flight line recovery onto maps.

In the next year, 1948, the USGS completed aeromagnetic survey within an area containing the west half of the Mesabi Iron Range plus an area of potential eastward extension of the Cuyuna Iron Range. The 1948 flights had similar design to the 1947 work, except that lines were flown midway between section lines. In 1949, USGS flights covered the eastern end of the Mesabi Iron Range and the iron formations in the Tower-Ely (Vermilion Greenstone Belt) area, plus a substantial portion of the Duluth Gabbro basal zone. The 1949 flight lines were flown along section lines as was done in the 1947 flights. The east edge of the 1949 survey area came near, but did not quite touch the initial sites of 1948 base metal copper-nickel mineralization discovery in the Duluth

Gabbro. A subsequent USGS flight in 1951 added this discovery area. By 1955, most of the north half of Minnesota was covered by USGS aeromagnetic reconnaissance (1-mile line spacing) survey.

More USGS flights were undertaken in Minnesota in the 1960's and USGS achieved first generation statewide aeromagnetic coverage of the state in 1966, in total flying and collecting nearly 84,000-line-miles (~135,000 line km) of profile data using 1-mile flight line spacing and mean terrain clearance of 1,000 feet (500 feet clearance in a few survey blocks, plus one small spot of wider-spaced east-west oriented lines in Pine County). In order to summarize all of this work, USGS, in 1970, in cooperation with the Minnesota Geological Survey released a statewide aeromagnetic map (Zeitz and Kirby, 1970). MnDNR has on file a nearly complete set of the maps and profiles published during this 20-year effort, and most of these maps are available for download through USGS. Figure 1 shows the acquisition timing of USGS first generation aeromagnetic flights in Minnesota. Additional summary information about publication vintage and map series of geophysical investigations in Minnesota can be found in Beltrame (1978).

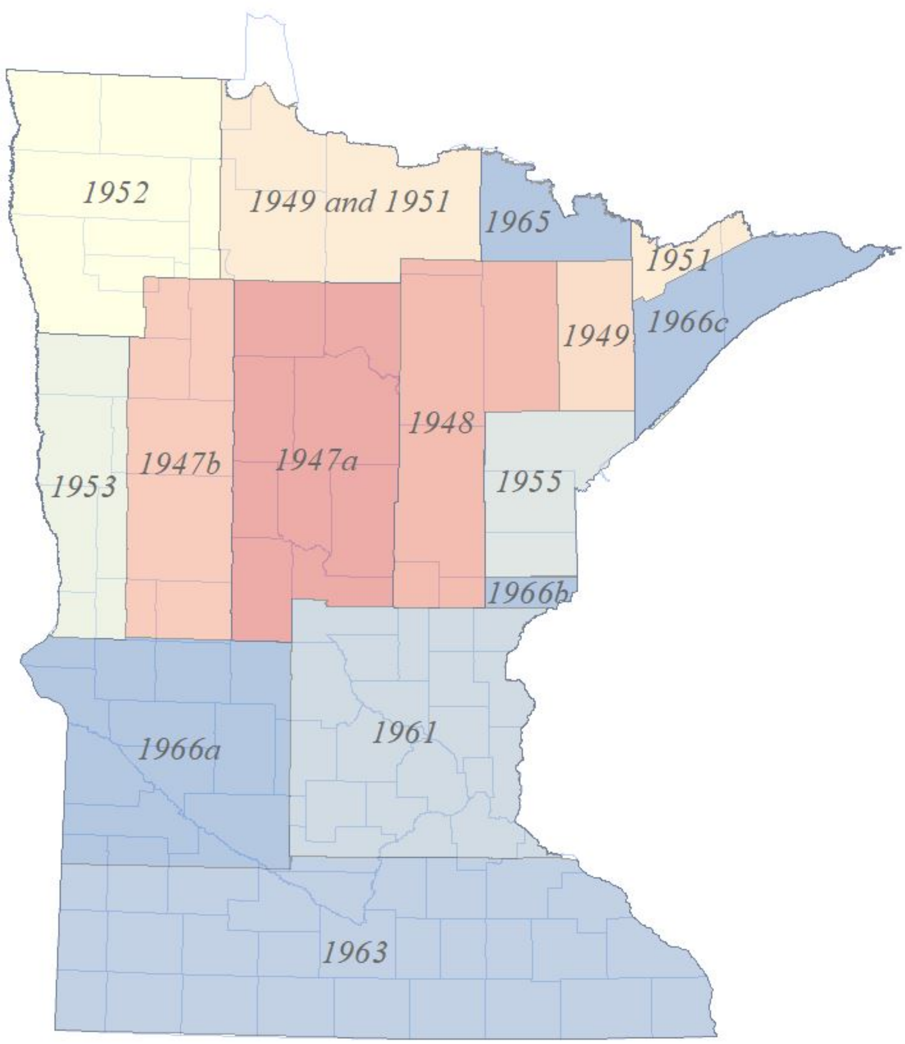


Figure 1. USGS first generation aeromagnetic data acquisition areas by year flown.

The regional magnetic trends outlined by this first generation of aeromagnetic survey revealed buried extensions of bedrock greenstone (volcanic) belt terrane, large intrusive bodies, details of the mid-continent rift, major structural discontinuities, and some previously undetected features. These first-generation government surveys and their pre-publication open-file map releases greatly influenced the timing and deployment of subsequent industry surveys. In fact, none of the industry airborne surveys on file at MnDNR precedes USGS survey at any location in Minnesota.

Mineral exploration and resource companies closely followed the progress of the USGS aeromagnetic work as it progressed, and in some cases, either used USGS open-file results directly for iron exploration projects, or used the open-file results to identify areas of interest for deployment of higher resolution, more detailed aeromagnetic and electromagnetic mineral exploration surveys.

Airborne electromagnetic (EM, or AEM) survey methods were first tested in 1948 in Canada and developed in the early 1950’s (Fountain, 1998). Fountain describes that the technique gained traction following detection of a mineral deposit in New Brunswick by airborne electromagnetic survey in 1954. Electromagnetic data were viewed as an additional anomaly filter when flown in conjunction with aeromagnetic survey. Pulsed electromagnetic survey techniques were developed by SELCO Exploration in the early 1960’s (Barringer, 1987) and spun off to Questor Surveys Ltd. and Geoterrex, Inc. (Witherly, 2000). Most of the airborne electromagnetic surveys on file at MnDNR are of the Mark V INPUT (INduced PUlse Transient) variety which was introduced by Barringer Research, Ltd. in 1965 (Barringer, 1987, see Figure 2). The earliest airborne electromagnetic survey on file at MnDNR is from 1954.

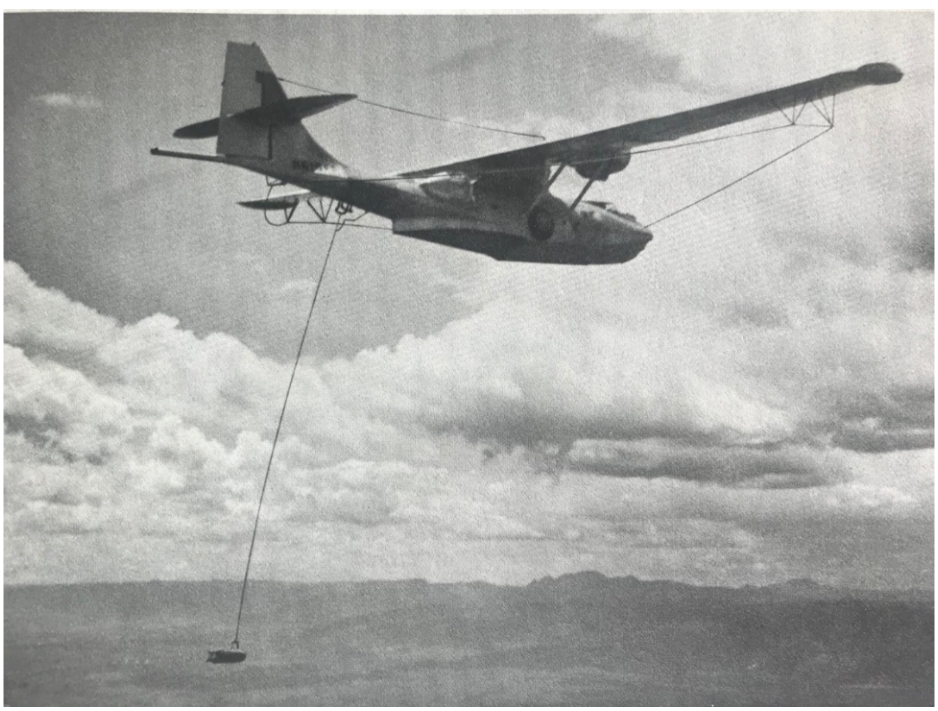


Figure 2. INPUT Mark V airborne electromagnetic survey platform in use. Image from Barringer (1965). Super Canso (PBY Catalina) aircraft with electromagnetic transmitter loop extending to wingtips, towed receiver "bird", and aft-mounted "stinger magnetometer".

Most industry airborne geophysical surveys in Minnesota were flown under contract and were deployed during regional reconnaissance stages of exploration programs, in order to better define geologic trends and to detect bedrock conductors (e.g., graphite-bearing rocks, iron formation, shear zones, other metallic minerals). Flight line spacing on industry surveys during this time period ranges from 1/8 mile to 1 mile, but most of the surveys are based on ¼ mile flight line spacing with aircraft mean terrain clearance at ~400 feet. Many of the surveys used customized flight line orientations to fly perpendicular to the regional grain of the USGS-detected bedrock trends.

Beginning in 1979 and over the next 12 years, the Minnesota Geological Survey contracted and acquired high-resolution, digital aeromagnetic coverage of the state, with funding from Minnesota's Legislative Commission on Minnesota Resources (Figure 3). These surveys were primarily flown using ¼ mile line spacing and mean terrain clearance of 500 feet (Chandler, 1991). According to Chandler (1991), USGS flew and contributed a portion of this second-generation flight work. Existing Geological Survey of Canada data were incorporated at the Minnesota portion of Lake Superior and Lake of the Woods, a large industry survey from southwestern Minnesota was donated for use, and first generation USGS data were re-used at the built-up Minneapolis-St. Paul metropolitan area.

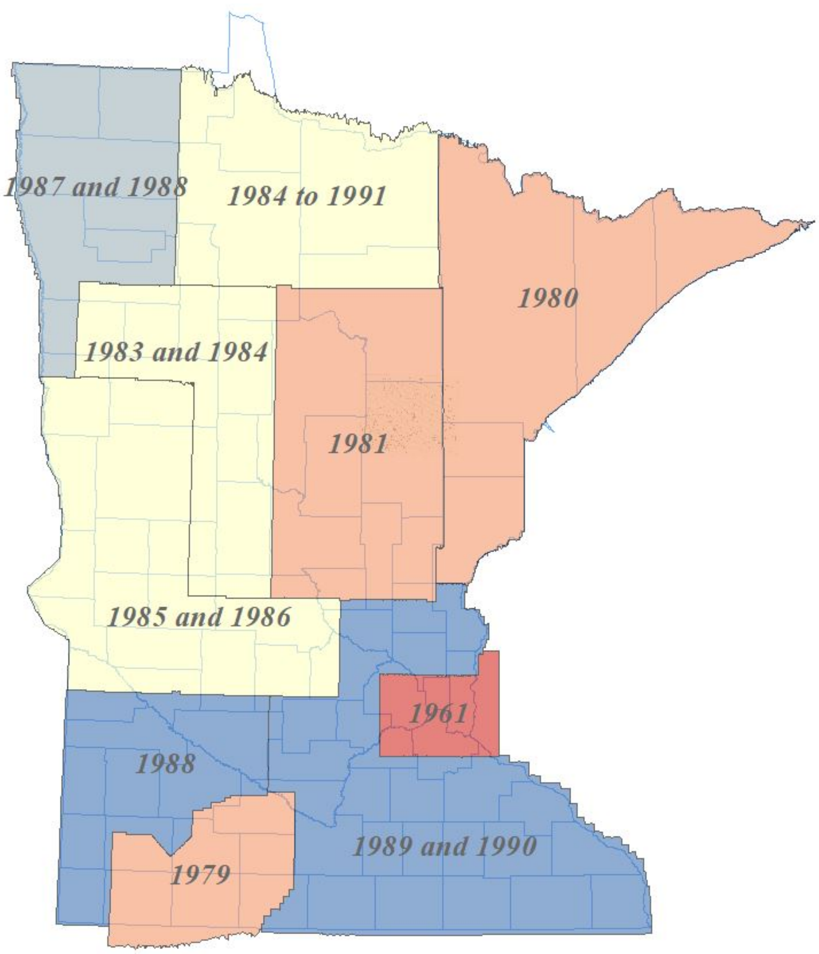


Figure 3. Acquisition dates for surveys and data used in Minnesota Geological Survey second generation efforts.

In similar result to the first-generation USGS aeromagnetic work, the MGS second-generation acquisitions were closely followed by mineral exploration companies, and in some cases the MGS results were used directly in exploration programs or were used (and still are used) as a guide to outline areas of interest for more detailed surveys. MnDNR has on file most of the published maps produced during this second generation effort, including quadrangle-based contour sheets, as part of the historical record. The primary products of the second-generation MGS work are digital files and derivatives, which are available for download through the Minnesota Geological Survey.

Hardcopy chart paper strip-log profiles and hand-contoured maps began to be supplanted by digital recording and plotting techniques in the late 1970's, marking the beginning of the transition from hardcopy to digital as the primary deliverable format for airborne surveys. Digital recordings were initially made on magnetic tapes, and these recording methods were migrated to other media as those technologies developed. Visual, Doppler radar, and LORAN-C (LOng RAnge Navigation) navigation and positioning methods eventually also were superseded by digital Global Positioning System (GPS) navigation systems. Hardcopy records as standard survey deliverables persist up through the mid-1980's in MnDNR files, with digital plotting and nine-track tapes showing up in the late 1970's, and fully digital records as deliverables after the 1980's. Previous tests on the old nine-track tapes have not succeeded in recovering data, and any information not previously converted is likely only available now as hardcopy, though the nine-track tapes are still held in archive.

Over time, many of the industry-contracted surveys have been donated to or acquired by MnDNR, and as noted above, this project has focused on rediscovering the surveys, enhancing their curation, and taking action to improve preservation and access to these fundamental data.

Inventory and Curation Methods

This section describes the methods and approach used to organize, scan and digitize the historical airborne geophysical surveys at MnDNR.

Hardcopy Handling

Initial prioritization and retrieval of survey deliverables at MnDNR relied on the senior author's familiarity with the exploration collections. Surveys were prioritized for curation based on completeness, physical vulnerability, project size and complexity, and to some extent geologic location of the survey. As each survey was retrieved for processing, maps were laid out and given an initial sort to determine full set completeness, and contractor or project reports were sought out to serve as orientation to each survey, before handing off for further organization, curation and cataloging. Materials segregated for curation in this step were limited to contractor deliverables and other materials directly related to surveys. Documents derived from survey data, such as maps showing survey results merged with other geological, geochemical, geophysical or ownership data, or additional follow up interpretation products, continue to be held in the exploration project record.

In curation, the deliverables from each survey were unpacked and organized, cleaned as necessary, and the often times poor quality boxes and containers holding the deliverables discarded. Poorer quality exact duplicate materials occasionally encountered were segregated and marked for later discard (contingent on successful curation and digital backup of highest quality originals). The materials were then organized as documents and each document assigned a unique collections ID. These ID's, were then penciled onto each document to ensure that even if label adhesives fail at some future date, the collections ID will persist on each hardcopy document. Use of pencils ensured that the collections ID will not stain or fade but is still reversible in case of error. The collections ID is a 7 digit integer number that serves as the primary key for both the physical materials and for subsequent digital versions of documents. The collections ID series begins at the number one million and one (1 000 001), with the leading 1 serving to help in sorting if ID's are handled as text; the 7 digit length is used in expectation that the total document count in all of the collections will not exceed 9 million.

Cataloging

As curation of each survey proceeds, each document is assigned the next available collections ID, and attributes of each document are cataloged about source, lineage, physical format, and thematic content. An internal document management system was established to support collections cataloging work (Olson, 2021), providing for controlled values, dropdown lists, definitions, formatting consistency and edit tracking, with function included for export, to transfer content into web-based or spreadsheet-based applications.

Upon completion of collections ID assignments and cataloging intake, labels are printed with collections ID, company name, project name, site name, and storage location. These labels are affixed to each document for permanent storage, usually before scanning. Oversize map documents are assigned to vertical or flat file map cabinets, and other materials to archive-quality office boxes for storage on a mobile (space efficient) shelving system. The labels used on airborne geophysical survey documents have used a green stripe on white background. Future collections labels will likely use a white label, as the colored stripe uses color bandwidth when scanned images are stored as color indexed files.

Scanning

Maps, reports and other documents amenable to scanning are scanned to PDF/A (A for Archive) format at 300 dpi (ppi), and maps are additionally saved directly to color-indexed TIFF format at the scanner. Scanning the volumes of flight line profile documents has been deferred until a separate scanning project can be funded for those documents. PDF/A and TIFF image formats were chosen for their relatively lossless storage, and single-band indexed color formatting was chosen to reduce the large file sizes otherwise attributable to discolored background on paper and mylar media. Scanned files were saved to temporary network directories for proofing and error correction, if needed, before placement in final long-term network storage. Additional information and discussion about scanning procedures, calibrations, equipment, format selections, filtering and color indexing can be found in Appendix A of this report.

Georeferencing

Scanned maps are georeferenced to UTM Zone 15, NAD83 using ArcGIS software. Many digital geographic products in Minnesota use an extended version of UTM zone 15 (the western and eastern margins of the state lying outside zone 15 are also cast as zone 15), in order that statewide information be shown in a single UTM coordinate projection. That practice has also been applied for georeferencing in this project. Four georeferencing links were established for each map using digital orthophotos, USGS 7.5-minute topographic quadrangle maps, or other base maps to match base characteristics of survey maps. In a of couple instances, magnetic anomalies on the MGS second-generation digital aeromagnetic coverage have been relied on as reference points in areas of very poor base map quality. Four point registrations (as opposed to 2 or 3 point) are used to ensure that georeferencing results are not being overly influenced by individually misaligned pieces of survey photomosaic base maps or other base map distortions. Georeferencing links are saved to a links file so that the original image is still preserved, rather than rectifying the scanned maps as a completely new set of derivative imagery.

Producers and sponsors of these airborne surveys understood the positional uncertainties associated with uncontrolled photomosaic base maps and available flight line plotting methods, and they understood that anomalies plotted on survey maps were subject to follow up ground work to fully establish anomaly positions. This is important to recognize in context of georeferencing and reuse of the historical surveys. Considerable effort has been applied to georeferencing the maps in this project, but there is a point at which substantial additional effort only results in higher precision rather than higher accuracy. Georeferencing efforts beyond four point registrations, such as higher order transformations, re-projecting, or translating survey fiducials to modern orthophoto base maps have not been pursued as part of this project. The scanned and digital products reported here might be used as a starting point for that kind of detailed work, since the original unreferenced images are directly available for use, but that level of detailed effort is likely applicable only at very specific anomaly locations. These uncertainty considerations also apply to digitized flight lines.

Digitizing

Flight lines that are depicted on survey maps show the path of the aircraft and the ground trace of resulting survey profiles that constitute the actual collected survey data. In this project, flight line traces are digitized from the georeferenced maps in order to provide a spatial index to the profile documents, and to serve as building blocks for constructing survey area footprints. The digitized lines also provide a means of generating summary statistics about surveys such as total line kilometers and number of flight lines encountered in a survey.

Flight line digitizing has been conducted using ArcGIS software, with maps displayed onscreen at approximately 2x that of hardcopy map scale. For instance, flight lines portrayed on 24,000 scale maps are displayed at approximately 12,000 scale during digitizing, slightly coarser if survey maps have high cartographic quality, and more detailed if map quality is low or if flight line fiducial postings on maps are within digital snapping tolerances.

In most cases, lines are digitized as a series of points corresponding to the fiducial points and non-fiducial line direction changes, as plotted on the survey maps. In a few cases of very dark map reproductions or other poor map quality, points are digitized along lines as can be recovered. In some of the more recent survey maps, particularly helicopter-borne surveys, the detail plotted from digital navigation systems far exceeds reasonable index digitizing, and digitizing in those cases has been confined to representation at 2x magnification of the hardcopy map scale.

Flight line attributes include company name, project name, survey name, site name where applicable, placeholder attributes for line ID and flight line direction, and GIS-calculated line lengths.

The area-of-acquisition footprints for the survey areas are generated from the digitized flight lines, by buffering the flight lines of each survey using a buffer distance equal to each survey's designed mean flight line spacing. In portions of surveys where every other or every fourth flight line interval was flown for reconnaissance purposes, survey footprints take on a multi-part expression. Survey footprints constructed in this manner accurately capture coverage extent associated with extended length flight lines and tie line lengths, and gaps in survey coverage.

Survey area attributes include company name, project name, survey name, site name, line kilometers flown (GIS), number of flight lines (GIS), geophysics type, survey contractor, date flown, survey technique, survey orientation direction, mean line spacing in feet and meters, mean terrain clearance in feet and meters, survey target, number of map tiles, tile type, total number of map sheets in inventory, map scale, base map type, number of multi-tile composited maps, profiles status, collections ID for the report or map reference supplying the survey attributes, and a list of collection ID's of the survey maps.

A map tiles index is then derived from the survey area footprints, by subdividing the survey area footprints along tile boundaries and adding tile attributes for each resulting tile polygon. These additional tile attributes include tile ID, tile name, and map collections IDs by map type. These map tile footprints and the tile ID attribute will be useful if mosaic image display or mosaic image production is desired.

An overall index of inventoried airborne geophysical survey documents has been generated, by exporting inventory information from the internal document management system to a comma separated value (.csv) format and then loading the .csv file into an Excel spreadsheet format. As web-based applications are deployed to better access and download the underlying source documents, the Excel spreadsheet may eventually become superseded by online products, if errors or additional documents are discovered.

Shapefiles and Spreadsheets are listed in Appendix B and are included as a data files package that accompanies this report.

Results

Figure 4 illustrates the cumulative footprints of the 133 surveys inventoried, curated, scanned and digitized during the current project. Information that is much more detailed is provided in the accompanying index shapefiles. Tables 1 and 2 summarize a few of the attributes recorded in the shapefiles. For detail, see the shapefile attributes and equivalent Excel spreadsheet version listed in Appendix B. Together, these two tables provide an overview of the well-documented surveys that are on file as hardcopy at MnDNR. Many of these surveys have fully complete sets of deliverables on file. Some surveys are represented only as map sets.

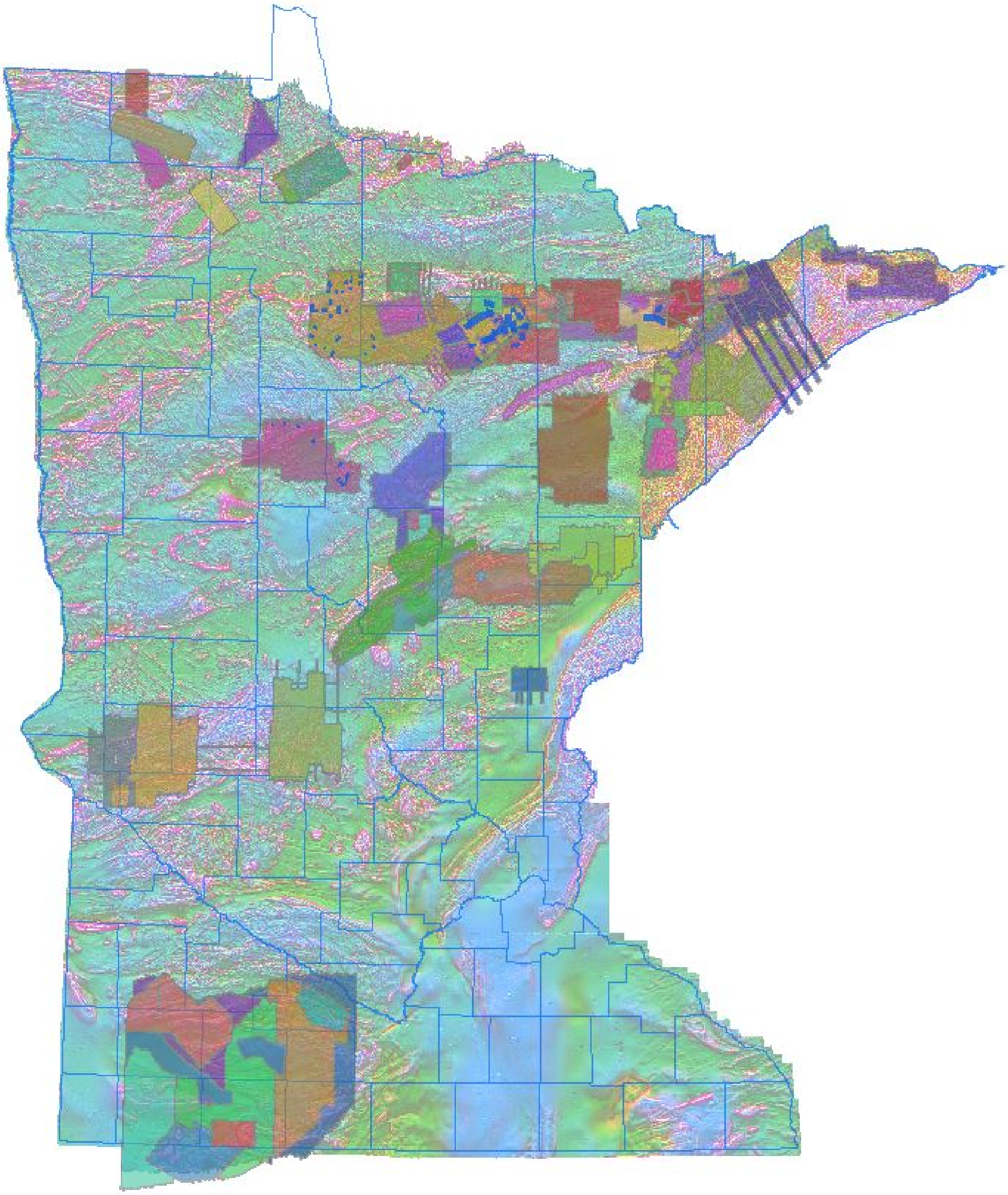


Figure 4. Acquisition footprints for 133 nongovernment hardcopy airborne geophysical surveys inventoried during current effort (colored polygons), superimposed on a 3-band (slope-curvature-intensity) image of Minn. Geological Survey second-generation digital aeromagnetic data (Dahl, in prep).

Table 1. Regional Airborne geophysical surveys inventoried during current project work.

Survey No.	Date Flown	Survey Name	Line Km	Flown For	Targeted At
1	1951-05-XX	Aitkin County Sulfides Area	6,821	Hanna Mining	Sulfur
2	1951-06-XX	Cuyuna Range Area	4,058	Hanna Mining	Iron
3	1952-XX-XX	Cuyuna - NE Crow Wing	1,937	United States Steel	Iron
4	1954-03-XX	Cuyuna Range Area - Emily	423	Hanna Mining	Iron
5	1954-XX-XX	Cuyuna - E Cass County	3,038	United States Steel	Iron
6	1955-05-XX	Cuyuna - Emily Test Area	125	United States Steel	Iron
7	1955-11-XX	Allen Area	37	Bear Creek Mining	Base metals
8	1955-XX-XX	Cloquet Valley Area -	632	Bear Creek Mining	Base metals
9	1955-XX-XX	Kawishiwi River Area	174	Bear Creek Mining	Base metals
10	1958-07-XX	Babbitt Area	737	Bear Creek Mining	Base metals
11	1963-11-XX	Mesabi Range Area	817	Hanna Mining	Iron
12	1966-04-XX	Area I	1,747	United States Steel	Base metal sulfides
13	1966-04-XX	Area II	926	United States Steel	Base metal sulfides
14	1966-04-XX	Area III	182	United States Steel	Base metal sulfides
15	1966-12-XX	Northeastern MN Test	162	Hanna Mining	Base metals
16	1967-01-XX	Duluth Gabbro Area	453	Lindgren & Lehmann	Cu-Ni sulfides
17	1967-01-XX	Area II - North	1,615	United States Steel	Duluth gabbro minerals
18	1967-01-XX	Area II - South	1,797	United States Steel	Duluth gabbro minerals
19	1967-03-XX	Cook County Area	2,591	New Jersey Zinc	Duluth gabbro minerals
20	1967-03-XX	St. Louis and Lake Counties	1,882	New Jersey Zinc	Duluth gabbro minerals
21	1967-06-XX	Duluth Project	1,320	Phelps Dodge	Base metals
22	1967-10-XX	VermEly Area	5,587	Bear Creek Mining	Base metals
23	1967-11-XX	Snowbank Lake Area	533	Amax Exploration	Base metals
24	1967-12-XX	AFMAG	1,189	Amax Exploration	Base metals
25	1968-05-XX	Linden Area	542	Hanna Mining	Base metal sulfides
26	1968-05-XX	Togo - Big Fork Area	2,384	Hanna Mining	Base metal sulfides
27	1968-09-XX	Milestone JV - Cook Area	1,669	W.S. Moore	Massive sulfides
28	1969-03-XX	Milestone JV - Bear Lake	1,711	W.S. Moore	Massive sulfides
29	1969-03-XX	Milestone JV - Bergville	1,248	W.S. Moore	Massive sulfides
30	1969-03-XX	Milestone JV - Bigfork Area	2,389	W.S. Moore	Massive sulfides
31	1969-03-XX	Milestone JV - Effie Area	622	W.S. Moore	Massive sulfides
32	1969-03-XX	Milestone JV - Grygla Test	201	W.S. Moore	Massive sulfides
33	1969-03-XX	Milestone JV - Mizpah	675	W.S. Moore	Massive sulfides
34	1969-03-XX	Milestone JV - Roseau Test	164	W.S. Moore	Massive sulfides
35	1969-04-XX	Milestone JV - Baudette	1,650	W.S. Moore	Massive sulfides
36	1969-06-XX	Cook Area	2,682	United States Steel	Massive sulfides
37	1969-06-XX	Ely Area	1,207	United States Steel	Massive sulfides
38	1970-02-XX	Itasca County Area	2,958	United States Steel	Massive sulfides
39	1970-05-XX	Ely Area A	663	Hanna Mining	Massive sulfides
40	1970-05-XX	Ely Area B	211	Hanna Mining	Massive sulfides

Survey No.	Date Flown	Survey Name	Line Km	Flown For	Targeted At
41	1971-03-XX	Lake County Area	4,997	United States Steel	Base metal sulfides
42	1971-03-XX	Rice Lake Test Area	70	United States Steel	Massive sulfides
43	1971-XX-XX	Fernberg Area	688	Hanna Mining	Base metals
44	1971-XX-XX	Togo - Big Fork Area 2	651	Hanna Mining	Base metals
45	1971-XX-XX	Vermilion Area	100	Hanna Mining	Base metals
46	1974-11-XX	Aitkin - Carlton County	5,081	United States Steel	Massive sulfides
47	1974-11-XX	Meadowlands Area	2,847	United States Steel	Massive sulfides
48	1975-04-XX	Babbitt Area INPUT Test	121	Amax Exploration	Base metal sulfides
49	1977-04-XX	Moose Lake Area - 1977	673	Rocky Mountain Energy	U/graphitic conductors
50	1977-10-XX	Melrose Area	5,244	United States Steel	Massive sulfides
51	1977-10-XX	Morris Area	5,692	United States Steel	Massive sulfides
52	1978-02-XX	New Ulm Area	4,152	Pan Ocean Oil	Uranium
53	1978-04-XX	Moose Lake Area - 1978a	1,143	Rocky Mountain Energy	U/graphitic conductors
54	1978-10-XX	Garrison Area	642	Kerr-McGee	Base metals
55	1978-10-XX	Mud Hen Area	354	Kerr-McGee	Base metals
56	1978-11-XX	McGrath Gneiss Area	1,859	Anaconda Copper	U/graphitic conductors
57	1978-11-XX	Moose Lake Area - 1978b	2,317	Rocky Mountain Energy	U/graphitic conductors
58	1978-11-XX	Mora Area	383	Rocky Mountain Energy	U/graphitic conductors
59	1979-03-XX	Sioux Quartzite Magnetics	22,534	Pan Ocean Oil	Uranium
60	1979-08-XX	Sioux Quartzite Area - Blk 1	5,400	Pan Ocean Oil	Uranium
61	1979-08-XX	Sioux Quartzite Area - Blk 2	7,719	Pan Ocean Oil	Uranium
62	1979-08-XX	Sioux Quartzite Area - Blk 3	4,773	Pan Ocean Oil	Uranium
63	1979-08-XX	Sioux Quartzite Area - Blk 4	6,575	Pan Ocean Oil	Uranium
64	1979-08-XX	Sioux Quartzite Area - Blk 5	2,940	Pan Ocean Oil	Uranium
65	1979-08-XX	Sioux Quartzite Area - Blk 6	925	Pan Ocean Oil	Uranium
66	1979-08-XX	Sioux Quartzite Area - Blk 7	1,084	Pan Ocean Oil	Uranium
67	1979-12-XX	Yggdrasil - Greenbush Area	1,823	Houston Oil & Minerals	VMS, precious metals
68	1979-12-XX	Yggdrasil - Thief River Area	864	Houston Oil & Minerals	VMS, precious metals
69	1979-12-XX	Yggdrasil - Warroad River	1,123	Houston Oil & Minerals	VMS, precious metals
70	1980-01-XX	Polaris JV - Hubbard Area	4,465	E.K. Lehmann & Assoc.	Base metals
71	1980-01-XX	Polaris JV - Sturgeon Area	11,957	E.K. Lehmann & Assoc.	Base metals
72	1981-11-XX	Milestone JV - Oaks Corner	817	W.S. Moore	Massive sulfides
73	1983-10-XX	Itasca County Project	5,326	Meridian Land & Minerals	VMS, precious metals
74	1988-03-XX	Birchdale Area	508	Normin Mining	Base and precious
75	2008-01-XX	Winterfire Project	13	Prime Meridian Resources	Base and precious

Notes on Table 1:

- Date Flown entries are formatted in Library of Congress Extended Date Time Format (ETDF), which allows for imprecision or uncertainty in dates to be represented using an “X” character. In those cases where surveys have acquisition dates spanning more than one month, the month of greatest acquisition is listed as the Date Flown.
- Line Km is the sum of line kilometers digitized as flight line lengths for each survey.

Table 2. Fifty-eight detail airborne (Helicopter Electromagnetic, HEM) geophysical surveys associated with the Polaris Joint Venture project, deployed after regional airborne surveys in the Ely, Hubbard and Sturgeon areas of northern Minnesota.

Survey No.	Survey Name	Line Km	Project	Flown For
76	E-1 (Skeleton Lake)	389.9	Polaris JV - Ely	E.K. Lehmann & Assoc.
77	E-2 (Needle Boy Lake)	96.7	Polaris JV - Ely	E.K. Lehmann & Assoc.
78	H-3-1 (Alcohol Creek)	27.0	Polaris JV - Hubbard	E.K. Lehmann & Assoc.
79	H-3-2 (Brisbane)	13.3	Polaris JV - Hubbard	E.K. Lehmann & Assoc.
80	H-5-1 (Kabekona)	36.1	Polaris JV - Hubbard	E.K. Lehmann & Assoc.
81	H-5-2 (Evergreen Cemetery)	32.2	Polaris JV - Hubbard	E.K. Lehmann & Assoc.
82	H-7-1 (Cyphers Lake)	49.9	Polaris JV - Hubbard	E.K. Lehmann & Assoc.
83	H-8-1 (Boy Hiram)	27.3	Polaris JV - Hubbard	E.K. Lehmann & Assoc.
84	H-8-2 (Hackensack)	42.4	Polaris JV - Hubbard	E.K. Lehmann & Assoc.
85	H-8-3 (Paquet Lake)	78.2	Polaris JV - Hubbard	E.K. Lehmann & Assoc.
86	S-1-1 (Tolgen)	62.8	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
87	S-1-2 (Capernaum)	31.9	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
88	S-2-1 (Medicine Lake)	35.5	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
89	S-2-2 (Hay O'Brien)	128.0	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
90	S-2-3 (Phoebe)	47.4	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
91	S-2-4 (Detling Creek)	49.8	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
92	S-2-5 (Langor)	34.5	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
93	S-3-1 (Gull Lake)	38.4	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
94	S-3-2 (Rita)	16.8	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
95	S-3-3 (Pimushe Lake)	54.5	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
96	S-3-4 (Beatrice)	14.4	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
97	S-4-1 (Hayden Creek)	24.8	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
98	S-4-2 (Meadow Creek)	29.8	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
99	S-4-3 (Bullhead Lake)	53.7	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
100	S-4-4 (Hoover Creek)	40.4	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
101	S-4-5 (Conan)	30.4	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
102	S-4-6 (Humble)	33.9	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
103	S-4-7 (Cormorant)	16.3	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
104	S-5-1 (Hornet)	14.6	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
105	S-5-2 (Inez)	79.3	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
106	S-6-1 (Funk Lake)	52.7	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
107	S-8-1 (Moose Lake)	22.0	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
108	S-8-2 (Third River)	27.2	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
109	S-8-3 (Morph Meadow)	18.9	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
110	S-9-1 (Pomroy)	31.5	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
111	S-13-1 (Galebrook)	73.5	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.

Survey No.	Survey Name	Line Km	Project	Flown For
112	S-13-2 (West End)	147.4	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
113	S-13-3 (Bustic Lake)	12.0	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
114	S-14-1 (Ruby Lake)	13.8	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
115	S-14-2 (Ghost Lake)	18.5	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
116	S-14-3 (Forest Lake)	20.0	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
117	S-15-1 (Klingenpiel Lake)	346.6	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
118	S-15-2 (Larson Lake)	25.1	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
119	S-15-3 (East End)	160.1	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
120	S-15-4 (Deer Lake North)	222.7	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
121	S-15-5 (Zeisser's Island)	315.0	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
122	S-16-1 (Anderson Lake)	208.2	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
123	S-16-2 (Highland Lake)	42.2	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
124	S-17-1 (Spring Bear)	221.2	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
125	S-17-2 (Holstrom)	180.7	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
126	S-17-2A (Holstrom Addition)	9.0	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
127	S-17-3 (Togo)	43.4	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
128	S-17-4 (Thistledew)	274.3	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
129	S-17-4A (Thistledew Addition)	21.7	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
130	S-17-4B (Thistledew Addition)	7.5	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
131	S-18-1 (Wamp Lake)	111.1	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
132	S-18-2 (Sherry Lake)	120.6	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.
133	S-18-3 (Kathryn)	11.0	Polaris JV - Sturgeon	E.K. Lehmann & Assoc.

Notes on Table 2:

- Line Km is the sum of line kilometers digitized as flight line lengths for each survey.

Figure 5 identifies as points the vicinity locations for another 30 historical airborne geophysical surveys noted during the inventory work. For these surveys, insufficient record exists in MnDNR files to generate descriptive entries or build survey footprints. However, enough information is present to identify that surveys were run in a general vicinity and to give some sense of survey location, even though the configuration and extent of the surveys are not entirely known. Twenty-six of the 30 surveys are identified through coarse index maps, small data snippets, or report narratives found in exploration documents on file at MnDNR. The other four points are included based on geographic clusters of similarly-named ground exploration sites on file at MnDNR. Table 3 lists cursory information for these 30 lesser known surveys.

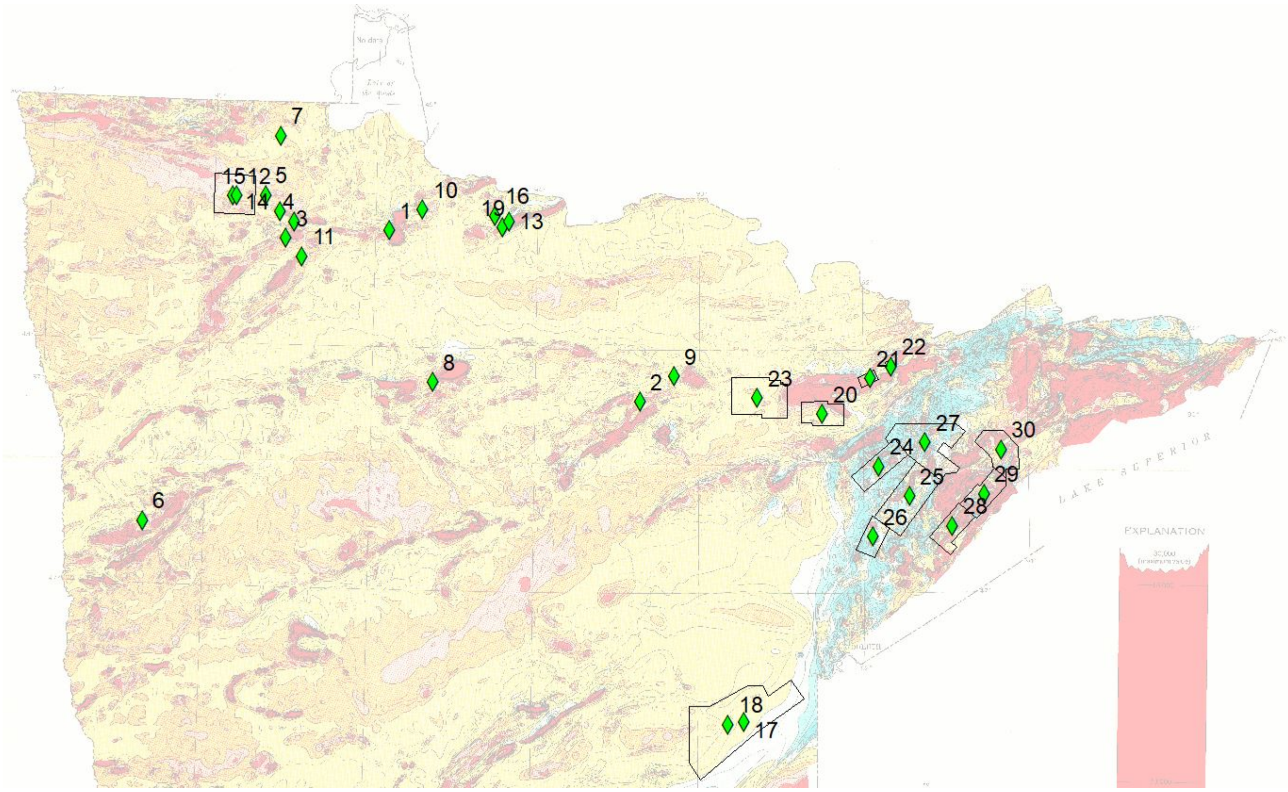


Figure 5. Vicinity locations of other airborne geophysical surveys identified in MnDNR files. Numbered points as listed in Table 3. Polygons correspond to index/overview maps. Background image from USGS Aeromagnetic Map of Minnesota (Zeitz and Kirby, 1970).

Based on sizes and extents of the known curated surveys, one might expect that these lesser-documented surveys would have extents covering 10-20 townships (2,500 – 5,000 line kilometers) each, but may be as small as 1 township in size or as large as 30 townships in size. The polygon outlines that are depicted in Figure 5 correspond to index or overview maps found in MnDNR files.

As governmental surveys, the statewide USGS and MGS first- and second-generation airborne data are not included among the tables of regional, detail, and lesser-documented surveys, except that the industry survey donated to MGS is included as a regional survey. USGS maps and profiles on file at MnDNR have been scanned and georeferenced for MnDNR use. These maps and data have been published to the web by USGS and MGS, respectively.

In total, 179,476.42 line-kilometers of flight lines have been digitized during this project (9,080 lines in the flight lines index). An additional ~533 line-kilometers and 50 flight lines are estimated from one aeromagnetic survey (Snowbank Lake) that did not have flight line traces posted (the estimate is based on the contoured data extent and ¼ mile spacing detail that is apparent in the contour work).

Table 3. Other airborne surveys identified during current project work. Insufficient information is available at present to build descriptive summaries or acquisition extents for these surveys.

Map Number	Flown For	Survey Name	Approx. Year	Basis
1	INCO	Recon I	1969	data snippets
2	INCO	Recon III	1969	data snippets
3	INCO	Recon IV	1969	data snippets
4	Humble/Exxon	Thief	1971	narrative
5	Humble/Exxon	Mud	1978	narrative
6	Humble/Exxon	Clay	1978	narrative
7	Humble/Exxon	Wood	1979	narrative
8	Humble/Exxon	Red Lake	1972	narrative
9	Humble/Exxon	Cook?	1969	clustered sites
10	Humble/Exxon	Baudette?	1969	narrative
11	Ridge Mining	Fourtown	1971	clustered sites
12	Texas Gulf	Wannaska	1982	data snippets
13	Humble/Exxon	Rainy River?	1970	clustered sites
14	Phelps Dodge	Vermilion Fault?	1992	clustered sites
15	Phelps Dodge	Roseau	1992	clustered sites
16	Texas Gulf	Rainy River	1969	clustered sites
17	Energy Reserves	Kettle River	1978	narrative
18	Martin-Trost	East Central Minn.	1978	index map
19	Kerr-McGee	Birchdale?	1988	clustered sites
20	Kerr-McGee	Tower	1988	index map
21	Kerr-McGee	Burntside	1988	index map
22	Kerr-McGee	Ely	1988	index map
23	Kerr-McGee	Cook	1988	index map
24	E.K. Lehmann & Assoc.	Billiton Gabbro Blk 1	1981	Index map
25	E.K. Lehmann & Assoc.	Billiton Gabbro Blk 2	1981	Index map
26	E.K. Lehmann & Assoc.	Billiton Gabbro Blk 3	1981	Index map
27	E.K. Lehmann & Assoc.	Billiton Gabbro Blk 4	1981	Index map
28	E.K. Lehmann & Assoc.	Billiton Gabbro Blk 5	1981	Index map
29	E.K. Lehmann & Assoc.	Billiton Gabbro Blk 6	1981	Index map
30	E.K. Lehmann & Assoc.	Billiton Gabbro Blk 7	1981	Index map

Table 3 note:

- Survey names that include a "?" are not clearly named within available information, and are estimated from site identifiers and/or drill hole abbreviations. For instance, a clustered group of sites and drill holes associated with Humble/Exxon near the Rainy River, all having names starting with "RR", are expected to be related to an airborne survey named "Rainy River Area".

A total of 815 maps have been scanned and georeferenced, which are associated with 321 map tile footprints (the map total includes 759 maps from non-government surveys and 56 maps from 1st generation USGS work). All but eight of the surveys listed in Table 1, and all of the surveys listed in Table 2 contain Electromagnetic (EM) data. Six of the surveys listed in Table 1 have mean flight line spacing less than 1,000 feet, and five surveys have mean flight line spacing of 2,640 feet (1/2 mile) or greater. All of the helicopter-borne detail surveys listed in Table 2 have mean flight line spacing of 400 feet.

Discussion

The rich detail contained in the inventoried surveys is much more than can be described in a single report. The main purpose of this project has been to discover, organize and make accessible these data sets. A few general observations can be made about airborne geophysical survey records in Minnesota, and some simple examples of data will help to illustrate the kinds of information available. Some of these observations and examples provide historical perspective and context, others point out potential for reuse of data in mapping, research and land management activities.

Historical Context

The timing of airborne geophysical surveys in Minnesota having hardcopy deliverables has been influenced by not only by date of technology availability, but also the course of discovery and commodity cycles. The first government surveys targeted at areas of potential iron and strategic metals occurrence. The first industry survey targeted sulfur in pyrrhotite bodies.

The detection of the Kidd Creek volcanic-hosted massive sulfide deposit in Ontario in 1963 by airborne electromagnetic techniques led to a surge of airborne surveys over similar rocks worldwide. First availability of Minnesota nonferrous mineral leases on state lands, beginning in 1966, along with availability of upgraded electromagnetic survey techniques, led to extensive magnetic-electromagnetic exploration surveys being deployed in Minnesota in the late 1960's through the 1970's.

Discovery of uranium deposits along graphitic footwall zones in Australia and Canada led to a series of airborne electromagnetic surveys being flown in southwestern and east-central Minnesota in the late 1970's, in search of similar graphitic, potential host zones (see contractor survey reports for the Moose Lake and Sioux Quartzite survey areas). The discovery of the Hemlo gold deposit in Ontario in 1982 led to resurgent interest in potential gold deposits in similar geologic settings in Minnesota, leading to some new detailed survey work as a result (see exploration correspondence from Houston Oil and Minerals northwestern Minnesota YGGGDRASIL project survey areas).

Survey designs have generally been based on known deposits and the deposit models available at the time of survey. Surveys initially were designed to trace longer formational type deposit trends, then were focused toward more isolated volcanic-hosted or structural-break type bodies, and eventually toward detailed surveys for gold-related features. GPS-based surveys, which have become the norm since the 1980's (not reported in this project) have used digital MGS second generation data as a guide, and have targeted base metals in the

Duluth complex (including deployment of airborne gravity survey methods), surveys in areas of early-stage midcontinent rift intrusions, regional survey of potential Sedex environments, and detailed regional surveys in greenstone belt areas that meet occurrence criteria for orogenic lode gold, magmatic nickel-copper-PGM, and volcanic-hosted massive sulfide deposits.

The Magnetics Base

After the USGS statewide reconnaissance work at 1 mile line spacing in the 1940's-1960's, industry surveys at ¼ mile line spacing provided substantial increase in resolution in select areas, to support exploration in those areas of interest. In large part, the historical aeromagnetic survey work represented in hardcopy is superseded by MGS second-generation digital data of equivalent or higher resolution. The historical aeromagnetic data may, though, offer extra insight into magnetic trends and anomalies, for instance in areas where industry surveys have been flown at orientations other than north-south (Figure 6) or at tighter line spacing. In Figure 6, a government survey (north-south lines, image) and industry survey (east-west lines, contours) show reasonable co-registration, and the data show similar results. Each respective data set does a better job of picking out anomalies oriented perpendicular to its respective flight lines. The digital data show higher sensitivity in areas of low magnetic relief. In this example, the historical data is helpful in seeing through corrugation in the digital data and in confirming the location and shape of the larger anomalies.

The historical aeromagnetic survey data in combined EM-magnetic surveys also useful as a means for cross checking positional location of historical EM anomalies against modern aeromagnetic data.

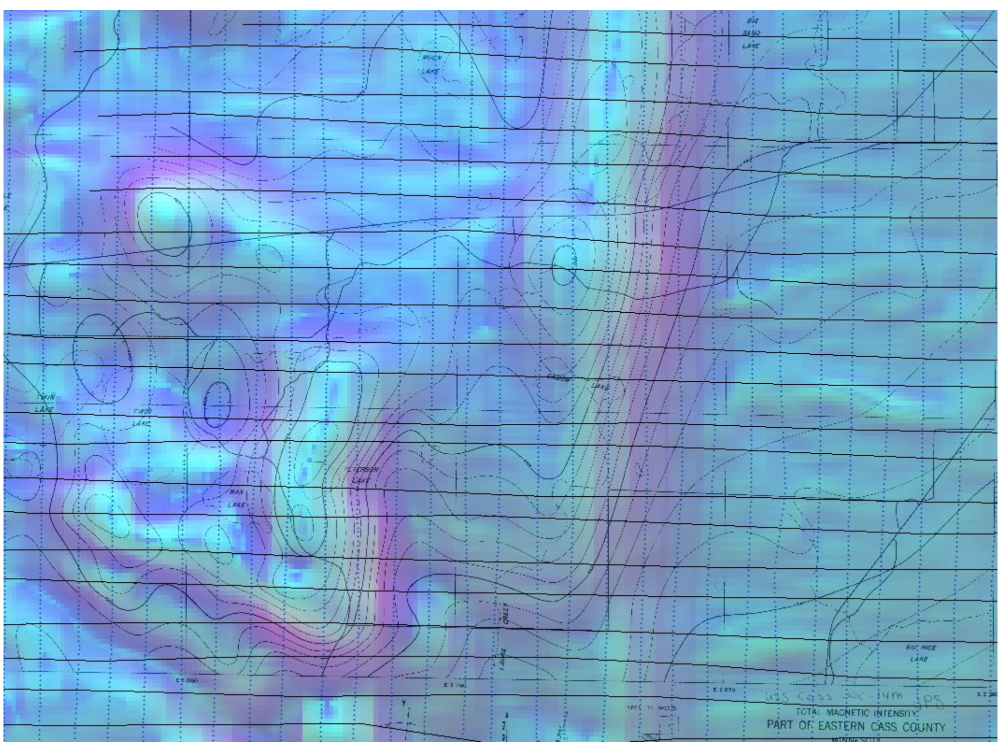


Figure 6. 1951 historical airborne survey data (black contours and east-west flight lines) from a survey between the Cuyuna and Mesabi Iron Ranges, superimposed on 3-band imagery of MGS 2nd-generation data having north-south flight lines.

Some historical aeromagnetic data has detected areas hosting mineralization, though not recognized at the time as such, for example at the Tamarack Intrusive Complex as shown in Figure 7. The USGS 1948 work flew directly over and fairly well outlined magnetic anomalies associated with intrusives containing currently delineated resources at Tamarack. The coverage of other historical surveys relative to an area of interest can also be useful in understanding exploration history in an area. For instance, at Tamarack a number of magnetic-electromagnetic surveys targeting other geologic features only incidentally touched the southern part of the Tamarack Intrusive Complex (Figure 8).

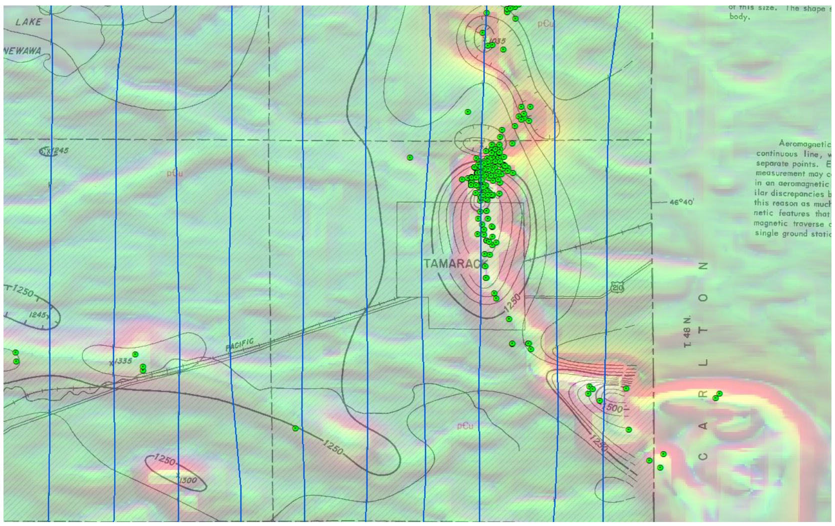


Figure 7. The Tamarack Intrusive Complex area in east-central Minnesota showing 1948 USGS flight line traces and magnetic contours superimposed on 3-band imagery of MGS 2nd-generation data, and recent drill hole locations (green dots).

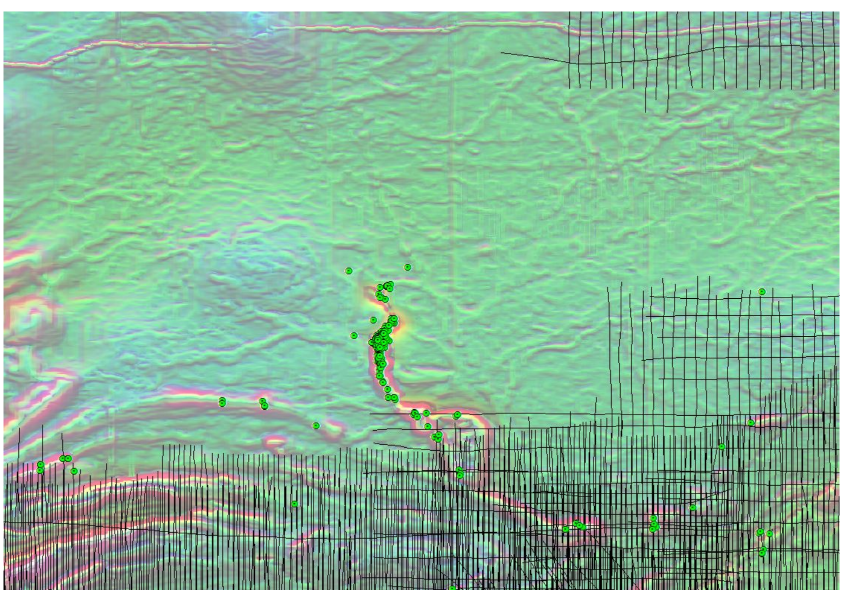
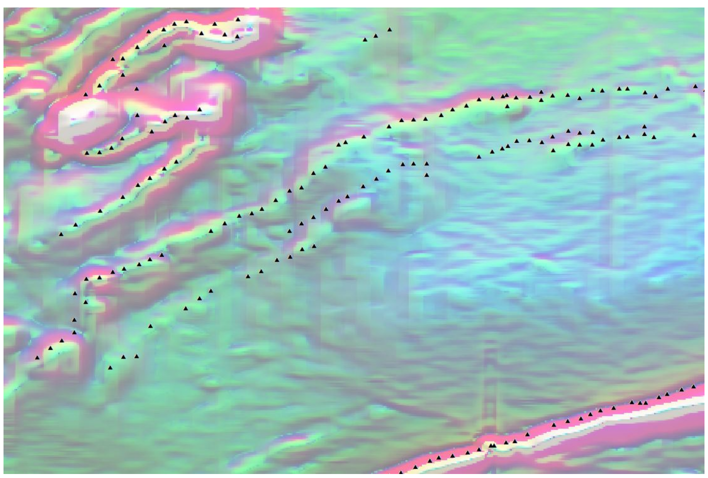


Figure 8. Distribution of historical airborne survey flight lines deployed in sulfur, base metal and uranium exploration near the Tamarack Intrusive Complex. For scale, flight lines are 1/4 or 1/2 mile line spacing.

Electromagnetic Data

Historical electromagnetic survey data, mainly interpreted in terms of bedrock conductors, may hold some value for characterizing overburden (surficial materials), such as for resistive gravel deposits within conductive overburden (Barringer, 1965). Historical electromagnetic data may also be useful in geological mapping exercises, providing unique or additional insight in areas of indistinct aeromagnetic expression (Lazenby, 1972; McSwiggen, 1987) and as shown in Figure 9. While the formational anomalies in the southeast and northwest part of the images (Denham and Glen formations, respectively) in Figure 9 carry both magnetic and electromagnetic expression, the peaks associated with the pair of conductors across the middle of the image have less apparent mappable magnetic expression, particularly the southern conductor of the pair, and the east end of the northern conductor (perhaps the pair represent unit repetition due to fold or imbrication?). The historical electromagnetic data may also be useful for conducting detailed review in areas of overlapping survey (Figure 10).



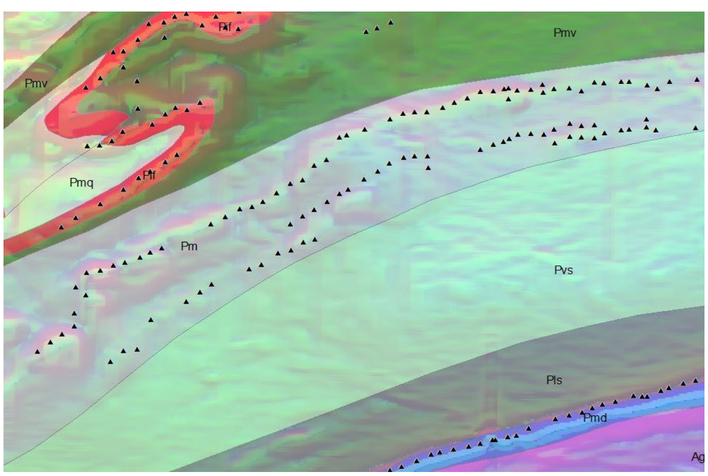


Figure 9 (upper image). Electromagnetic conductor peaks (black points) superimposed on MGS 2nd-generation imagery.
Figure 9 (lower image). Same area with MGS map S-21 bedrock geology map units. Conductor point spacing reflects 1/4 mile flight line spacing.

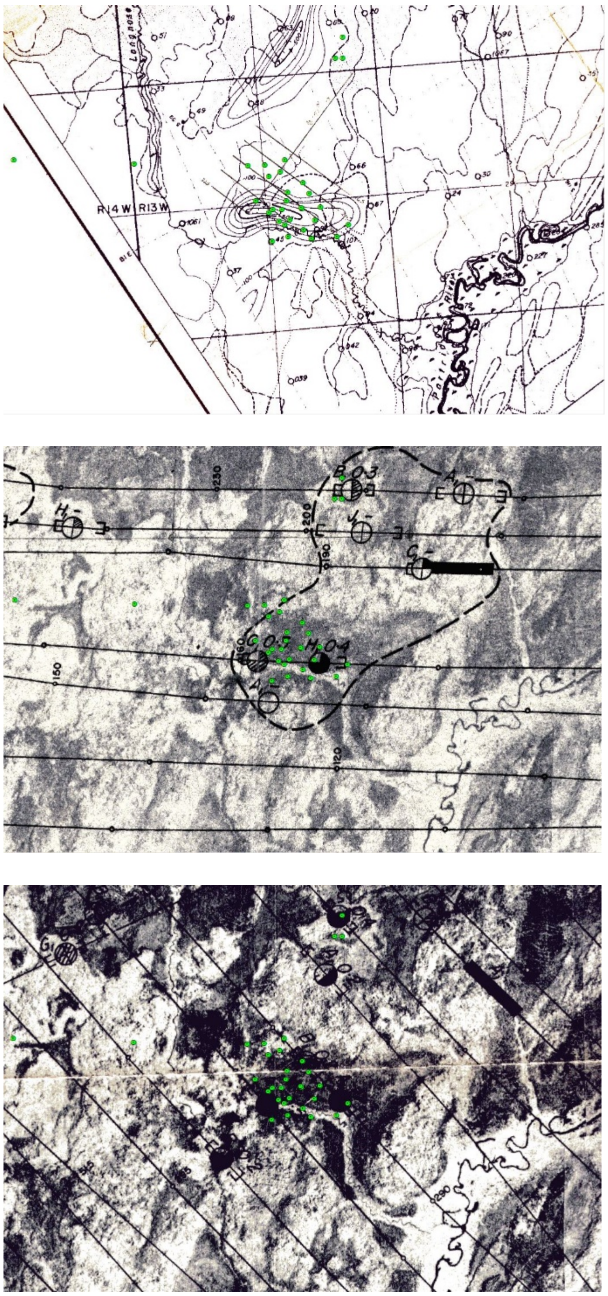


Figure 10. Airborne electromagnetic survey traces from three overlapping surveys at the Longnose oxide ultramafic location (drill holes as green dots). Top: 1958 out-of-phase anomaly (Bear Creek data). Middle: 1967 INPUT EM survey (U.S. Steel data). Bottom: Another 1967 EM survey (New Jersey Zinc data). Additional georeferencing has been applied to these detail areas to improve co-registration with orthophotos.

Other Known Surveys and Potential Future Donations into Public Domain

The 30 additional airborne geophysical surveys noted earlier may still exist in private holdings. These surveys might be viewed as targets for future donation into the public domain. Historical surveys in this category include survey blocks originally flown for Texas Gulf, Ridge Mining, Kerr McGee, Phelps Dodge, Humble/Exxon, Inco and perhaps Noranda in the Wabigoon Subprovince; by Humble/Exxon, Kerr McGee, Inco and Bear Creek Mining in the Wawa Subprovince; and by Cominco, Martin-Trost Associates, and Energy Reserves Group in the east-central Minnesota area. Additional content may exist for Bear Creek Mining and Phelps Dodge surveys along the base of the Duluth Complex where only partial coverage is on file at MnDNR, and E.K. Lehmann & Associates flew a large survey in the interior of the Duluth Complex. It is possible too that other historical surveys may exist for which there is no current evidence in MnDNR files.

More recent GPS-based, fully digital airborne magnetic and electromagnetic surveys are known to exist for parts of the Wabigoon and Wawa Subprovinces, Duluth Complex, the Mesabi Iron Range, and western part of Minnesota, including at least one airborne gravity survey in the Duluth Complex. Inventory and posting of information about these fully digital surveys remains for a future project.

Conclusions

Curation, scanning, digitizing and indexing of hardcopy airborne geophysical surveys on file at MnDNR has succeeded in enhancing inventory, knowledge of, preservation of, and access to hardcopy airborne geophysical survey maps and documents housed in DNR's mineral exploration archives. Locations of potential additional surveys not yet held in public domain have also been noted. The footprints of industry surveys in most cases outline the boundaries within which subsequent site level project work has been conducted during exploration programs, and these airborne survey footprints can serve as project "containers" when handling and evaluating other exploration program and site level data. The indexes (shapefiles) produced as part of this project provide for rapid orientation to the geographic extent of these historical data, maps and profiles, so that they can be considered and potentially reused during future survey mapping projects, university research, and agency land management activities.

Recommendations

As is the case for most projects, this one also concludes before available opportunities have been exhausted.

- The inventory status of flight line profiles on file at MnDNR, as a result of the current work, is well set up for continuation into a scanning project to both back up the fundamental data represented on the profiles, and to make the data more accessible. Conversion of the flight line profiles is foreseen as an exercise in producing PDF/A format documents. In some cases, the profiles are stored in folders (one or more chart traces per folder). These can be converted to one PDF per folder. Other profiles exist as flight line rolls containing multiple profiles in a continuous flight line scroll. Other profiles are stored in portfolio books, and some profiles are stored on microfilm rolls.

As profiles are handled and converted, the flight lines index shapefile can be updated to accommodate various ways that contractors have handled partial, infill or other nonstandard flight lines. The project outlined here would be a good match for a project funding proposal to the National Geological and Geophysical Data Preservation Program of the U.S. Geological Survey.

- For the most part, it is assumed that the early EM channels corresponding to overburden have not been examined in detail for information bearing on surficial materials composition other than noting surficial conductors. As noted earlier, EM data have in places been used for gravel deposit detection and for aquifer work. A pilot project to see if airborne EM data covering known aggregate deposit areas in Minnesota can distinguish those deposits would be an interesting test.

- Depiction of conductor peaks, half widths, channel ratios, conductor ratings, conductor zones, in phase/out of phase anomalies and other content, while uniform within a survey or a particular contractor's deliverables method, tend to have less uniformity across survey types and across contractors. While these features are contained in and are available on the map imagery, and are described in reports and can be extracted on an as-needed basis for specific future project needs, an effort to consolidate these aspects of data and anomalies into a GIS layer of conductor anomalies has not been undertaken.

- Additional opportunity exists to seek out donations or acquisition of the remaining hardcopy airborne geophysical surveys flown in Minnesota and not yet held in public domain. A project to determine the status of these survey deliverables and to see if they are available for donation may be a fruitful investment.

- Organization and curation of industry-sponsored GPS-based digital airborne geophysical survey files that have come into public domain in MnDNR files is also an obvious next project to bring the full suite of public domain survey data on file at MnDNR into availability for scientific, agency and industry reuse.

- Nearly all of the exploratory bore holes drilled in Minnesota have been deployed as a follow up to geophysical survey work. To attract additional interest in Minnesota's geologic terranes and exploration potential, the state would be well served to generate additional modern, pre-competitive data such as can be obtained by airborne geophysical survey methods (magnetic, electromagnetic, potentially gravity) as a means to enhance understanding of the state's geologic framework, to outline areas of potential mineral systems geological activity, and to attract exploration investment into the state.

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Appendix A: Large Format Map Scanning Settings and Procedures

Overview

The intent in making a large format scan of a drawing or map is to capture a digital image of the hard copy document, so that a backup is available in case of loss of the one-of-a-kind original, and so that the document is readily accessible for use from remote locations. To accomplish both goals, providing an archive copy in case of loss and providing remote access, the scanned document needs to be high enough in quality to serve the archive purpose, but small enough in file size to be accessed or downloaded from remote locations.

Historical mineral exploration large format documents tend to be line drawings or are line drawings overlain on aerial photo backgrounds. These documents occasionally have colored pencil or colored ink annotations, or symbols drawn on them. The use of full color photo backgrounds or other full color imagery backgrounds on historical hardcopy documents is rare within MnDNR mineral exploration archive collections. Published geologic or geophysical maps are present occasionally in the collections, and might also need scanning, where applicable, for reuse. Published maps tend to contain fine linework, solid color fill or textured colors, and text in various fonts. As a result, the published maps more refined cartography may require finer scanning requirements than typical hardcopy exploration drawings and maps.

Scanning, Quality, and Compression Concepts

Large format scans can make for very large file sizes when uncompressed (hundreds to thousands of megabytes). Various compression methods can be employed to reduce the file sizes of these scans. The key factor in most compressions is that they reduce the amount of file space needed to store image areas of uniform pixel values. Some compressions are “lossless” – they only compress truly uniform patches of pixels. Other compressions will take almost-uniform patches of pixels and force them to be uniform, at some loss of the original detail. These kinds of compressions are called “lossy” compressions.

Photo images tend to be harder to compress than linework and maps because whereas linework and maps tend to have large patches of uniform pixel values, in photos there are a lot of color gradients and intensity gradients, which make for only small patches having uniform pixels. Full color (24-bit) scans tend to produce the largest file sizes due to widespread gradients in content being present on three separate image bands (red, green and blue), within a single image.

The image complexity of linework drawings and maps encountered in historical mineral exploration collections is often low. These kinds of documents might best be characterized as monochrome linework having a few colors plotted on top, or linework plotted atop a photo backdrop, perhaps having a few colors plotted on top of that. Photo backdrops on historical mineral exploration documents tend to be degraded versions of the original grayscale aerial photography; the backdrops tend to contain much less detail than the original grayscale aerial imagery.

Knowing that image compression success depends on how uniform the image pixel values are, it follows then that a line drawing is much more compressible than a grayscale photo (huge patches of uniform background color in a line drawing can be compressed); and likewise, grayscale content is much more compressible than 3-band full color imagery (a single band of 256 intensity levels in a grayscale image is much less complex than a 3-band image where 16 million different colors are possible).

Ideally, for scanning most large format historical mineral exploration documents, we would like to routinely capture linework and associated photo backdrops, but also be able to include a few colors, not just grayscale. We would like to do this without requiring the large file sizes associated with full blown 24-bit color images. In between these two formats is an image processing technique that can be used to reduce the number of colors used in an image. Through use of a color palette, or color index, a color image can fit within a single-band image format. Large patches of uniform pixel values within images can be represented with very little coding, which in turn translates to better compression and smaller file size, with minimal loss of detail. In practice and experience, this middle of the road image format can produce a very useful and versatile product, a color indexed image.

Options for scanning large format historical mineral exploration drawings and maps boil down to either monochrome black and white, or grayscale (single band), or full color (three band), or indexed color. An indexed monochrome would essentially still be a monochrome image. An indexed grayscale would essentially still be a grayscale image. An indexed color image would be a color image stored on a single channel with a designated palette of available colors as an index to pixel values. This last format works well for drawings and maps that contain 256 or fewer colors – such as geologic maps or color annotated drawings. Color indexing of a full color 3-band 24-bit photo, however, would likely produce a less than satisfactory result, because a reduced number of colors would be unable to capture the many color and intensity gradients contained in the original 3-band imagery. But for all document types other than full color photo or high-quality grayscale photography imagery (which are rare within historical collections), a color indexed image format could potentially work well.

For imaging perspective, consider that USGS developed standards for scanning its 1:24,000, 1:100,000 and 1:250,000 scale topographic maps. These standards, developed in the mid-1990s, were updated in 2001. In the original standards, USGS used a 250-dpi color indexed image having 13 colors, stored in GeoTIFF file format, using packbits compression. USGS chose packbits compression at that time because the more effective LZW compression had proprietary restrictions. Under the original standards, average file size for a scanned 7.5 minute 1:24,000 scale topographic maps, covering both the map frame and surrounding collar area, was 8 Mb.

In 2001, USGS updated the standards for these kind of scanned map files. USGS chose to produce 500-dpi scans so that images could be further magnified or zoomed in before linework pixilation became noticeable. The earlier 1990's 250-dpi standard was originally chosen because of the cost of storage space and internet transmission rates available at that time. By 2001, those conditions had changed enough to support the larger file sizes associated with 500-dpi scans. These 500-dpi scans effectively allow very fine linework found on published topographic and geologic maps to stay coherent when zoomed in beyond 100% of original map scale. In the 2001 standards, USGS also allowed for expanding the number of colors in the color palette, when justified, to up to 256 colors, in custom palettes, in order to allow other kinds of USGS map products having additional colors to be scanned and displayed to look like the originals.

Dialing in Settings

In test scans at MnDNR, 300 dpi resolution (dots per inch, essentially same as ppi – pixels per inch) appears to resolve all of the needed detail on exploration archive drawings and maps. Scans at lower resolution (150-dpi) get pretty grainy, especially if linework is present in the document. Some archiving and preservation organizations recommend 600-dpi for scans, but in the absence of very, very fine line work, artistic brush strokes, or very fine faint handwriting (which is rare in exploration drawings and maps), 600-dpi does not seem justified. Adobe Systems chooses to downsample color and grayscale images to a 300-dpi default, and downsamples fine linework to 1,200-dpi when writing files for high quality printing. These parameters suggest that 300-dpi is sufficient for unpublished historical mineral exploration drawings and maps, adequately capturing color and intensity variations, and maintaining sufficient resolution to keep the fairly coarse linework on the maps from becoming grainy. For USGS-type published maps, such as the aeromagnetic geophysical map series of Minnesota we may decide that the USGS standard 500-dpi 256 color scans is most appropriate due to the fine linework present on these kinds of published maps. So far, for USGS' geophysical map series, that extra resolution and color bandwidth does not appear to be needed for MnDNR purposes.

The large format scanner presently in use at MnDNR (Contex 4250 with Nextimage 4.5.2 software) has the capability to do a number of image processing and cleanup steps at the point of scan, prior to compressing and saving the scan to a selected file format. This is an advantage over image post processing, since the scanned image can be manipulated to improve image pixel uniformity where justified, prior to compression. The color palette size for color-indexed images in the Nextimage software can be set in the range of 2-256 colors, and tests have been run at palette sizes of 256 colors, 64 colors, 32 colors, and 16 colors. The fewer the colors, the greater the compression result.

Surprisingly, for historical mineral exploration drawings and maps, color reduction to 32 colors appears to be reasonable for preserving photo backdrops plus a few colors, so that the saved image looks very much like the original. A larger 64-, 128- or 256-color palette might be justified in some cases, where high quality glossy grayscale photo paper is used to make an aerial photo backdrop, or in the case of a geologic map that contains many colors or many textured color fill symbols. But based on test results, a 32-color indexed image is sufficient to reproduce the line work, text and photo backdrops found in most exploration hardcopy drawings and maps. The intent for these scan products in MnDNR use is that they be useful as georeferenced backdrops in GIS displays, heads up digitizing, and general purpose serving, but not for detailed automated imagery analysis tasks or for automated extraction purposes.

Scanning to a color indexed image of a historical mineral exploration map is a preferable method to scanning a grayscale document, because then a user viewing the product will be able to unambiguously know for sure whether color was present on the original. A grayscale scan in itself is not capable of revealing whether there was color content on the original document. Most historical mineral exploration maps encountered in the hardcopy archives use degraded versions of air photos as imagery backdrops, so availability of a full 256 level gray spectrum is not critical for successful image capture of these maps. In most cases, a 32-color palette successfully captures both the photo backdrop, the linework and any color annotations present on the original. A color-indexed image is also preferable for monochrome originals, allowing for gray pixels to be assigned to pixels that fall partly on a line and partly on background.

The Nextimage software white point (auto) setting in tests has proven very useful for cleaning up yellowed background colors and reducing file size. The white point setting is expected to be used in most scans, except in cases where exceptional grayscale fidelity is already present in a document, such as in high quality grayscale prints of aerial photos printed on photographic paper (where white point is not helpful). In cases where the background color of a drawing is relatively dark, the white point setting should be manually adjusted to lighten the overall image and maintain the smallest file size possible.

File Formats

Options for saving scanned files basically boil down to JPEG, PDF, PDF/A, or TIFF formats. In tests of full color and grayscale images the JPEG, PDF, and PDF/A formats all produced essentially the same file size. TIFF and PDF/A can also produce small file sizes from color-indexed images. The advantage of PDF/A is that it is recognized as both an archival format and as a distribution format. It is readily shared and can include tags for searching and curation. The quality setting in PDF/A format only applies to grayscale and full color images that become compressed with JPEG-like compression. These quality settings do not apply to color indexed images, and since they make no difference in file size in indexed images they can be left at 100%. As a test of image file formats and to see what the quality setting actually does for 24-bit images, a 24-bit scan of the Ely-B test scan was saved in several ways. The results are shown below (JPEG 24-bit and PDF/A 24-bit compressions are comparable):

Table A-1. Comparison of image compression results using various scan settings.

Image Type	Quality Setting	Size Mb	File Size Change/ per 1% Quality Change	Compression Ratio
Uncompressed 24-bit	-	191.0	-	1
PDF/A 24-bit no autowhite	100%	52.7	-	4
JPEG 24-bit autowhite	100%	20.6	-	9
JPEG 24-bit autowhite	100%	11.2	-	17
JPEG 24-bit autowhite	99%	9.5	1.7 Mb	20
JPEG 24-bit autowhite	98%	7.6	1.9 Mb	25
JPEG 24-bit autowhite	97%	6.8	0.8 Mb	28
JPEG 24-bit autowhite	95%	5.5	0.7 Mb	35
JPEG 24-bit autowhite	90%	4.0	0.3 Mb	49
JPEG 24-bit autowhite	80%	3.0	0.1 Mb	64
JPEG 24-bit autowhite	70%	2.7	0.03 Mb	70
PDF/A 32clr autowhite	-	2.3		83
TIF-LZW 32clr autowhite	-	2.3		83

Tests on more complex photo background documents give compression and quality results similar to those presented above. This suggests that in those instances when full color or grayscale images are needed, a 98% quality setting can reduce file size by a third, but that additional compression below 98% quality is not as effective. Visual inspections of test scans also show that by the time an image is saved at 95% quality, finer linework starts to become blurry.

Interestingly, as highlighted on the last two rows of the above table, use of a 32 color indexed image with autowhite at 300 dpi, yields the highest compression – resulting in approximately 2.3 Mb images for PDF/A and TIF-LZW formats. The TIF-LZW format is a lossless compression. In tests, LZW compression consistently gave better compression results than packbits compression - 20% better than packbits in the case of 256 index colors and 45% better than packbits in the case of 32 index colors.

The preset for scanning most large format historical mineral exploration drawings and maps will be 300-dpi, indexed color, with autowhite, and a 32-color palette auto-generated for each scan, saved in lossless TIF-LZW format, and saved in PDF/A format with 100% quality setting. Scan instances requiring 90-degree rotation or mirroring as custom settings can have non-preset manual adjustments during scanning and will not be added to the scanner presets dictionary, but can be applied as necessary before saving the scan. In TIF-LZW format, a 32 color index image is about half the file size of a 256 color index image, and for most drawings shows very little visual difference, even if photo backdrops are present (since photo backdrops on the documents are much lower quality than 256 grayscale).

Alternative to the 32-color index expected to serve as the primary preset, presets will be also be saved for 64- or 256-color indexed images; and a preset with autowhite manually set to 100 and autoblack will be used for Mylar media – which autowhite seems to have problems with. Autowhite settings below 100 tend to degrade the hand-penciled document ID on the hardcopy and starts to degrade areas that have colored pixels. In tests, a Mylar image saved with 32 color index and autowhite setting yielded a 29.6 Mb image, while the same scan saved as a 32-color index image with white point manually set at 100 and with autoblack turned on yielded a 11.5 Mb, an almost two-thirds reduction in size compared to using only the autowhite setting on Mylars.

Assigning Settings, Image Names, Scanning, and Archiving the Hardcopy

MnDNR staff used the following procedures to scan large-format documents:

- Prep the scanner and network storage locations
    - Clean scanner glass as needed. If the maps are getting streaks on them from the scanner, the scanner requires cleaning. The cleaning instructions are in a pamphlet with the calibration template. The keyboard and monitor need to be removed prior to opening the scanner for cleaning. Follow the instructions to clean the scanner (there is a blue cloth to use, and dusting fluids should not be used if possible). Dusting off maps prior to scanning will prevent needing to clean the scanner as often. There are dusting materials located near the scanner.
    - Warmup and calibration of scanner. The scanner must be warmed up for about an hour to stabilize before use and calibrated prior to each day’s use. A folder near the scanner contains

    the scanner calibration template and instructions. Calibration takes about 15-20 minutes and the scanner will notify if calibration is unsuccessful. The calibration process is accessed through the Scanner Maintenance icon on the attached computer. When calibration is complete, the calibration template and instructions should be carefully returned to the storage folder. The scanner calibration template should be kept in the folder and kept clean and unfolded as much as possible as it is expensive to replace. The scanner should be left on always.

    - Ensure directory path is working and storage space is available at destination.
    - Verify scan quality:
        - At the beginning of each batch of scans, check the quality of the scan result carefully. Make sure images are not blurry, that all content is crisp and legible, and that no lines are offset due to unstitched scanner cameras.
        - Scan quality should be checked periodically during the day to verify that the scanner calibration has not changed.
- Set scanner to an appropriate preset or custom setting (see settings described previously).
- Set the scan file name to be the 7-digit Document ID found on the hardcopy document (usually written in pencil, or printed on a label).
- Prior to scanning the large format document, look for any tears in the hard copy that may cause the scanner to jam. Use Scotch Magic Tape on the back of the document, if necessary, as a temporary fix. Some curled maps may need to be fed into the scanner carefully in order to get them to engage the feed rollers in the scanner (for instance rolled glossy photo paper or rolled Mylar), or curled maps may need to be laid flat for a few days prior to scanning in order to flatten enough for scanning.
- In cases where a drawing or map is too wide to scan with north (up) at top, set the Nextimage software to rotate the scan back to upright before saving the scan result.
- If mirroring of a scan is needed (when document has content on both front and back as a “see through” method) that can also be accomplished before saving.
- White point should be set to Auto in most cases.
- When processing images, or in later steps like georeferencing where images are viewed in more detail, make note of any scans discovered to be not of sufficient quality. These can be rescanned before placing in permanent hardcopy storage.
- Save scan results to a local network directory.
- When placing document labels on maps prior to scanning, affix the label to what will become the upper left-hand corner of the document when hanging in storage, and place the label just below the strip needed for affixing the hanger. After scanning and proofing the saved TIF-LZW and PDF/A images, then add the vertical document hanger if needed, and add the large format hardcopy document to the vertical file or flat file map storage cabinet as appropriate. The document order used in each map cabinet is Document-ID number order.
- Independent proofing – batches of scans should be reviewed by an independent set of eyes to check for quality of scan products.

Appendix B: List of Shapefiles and Spreadsheets

Table B-1. List of shapefiles and spreadsheets related to Mineral Potential Project 407.

File Theme	File Name	Content
Index of Surveys	Index-of-Surveys.shp	polygons
	Index-of-Surveys.xslx	Spreadsheet of survey attributes
Index of Map Tiles	Index-of-Flight-Liines.shp	polygons
Index of Flight Lines	Index-of-Flight-Lines.shp	lines
Index of Documents	Index-of-Documents.xslx	spreadsheet
	Index-of-Documents.csv	Comma separated values format

Web-enabled access to the maps, reports and other scanned documents associated with the inventory work of this project will become available through a link at: https://www.dnr.state.mn.us/lands_minerals/mpes_projects/index.html

This report and associated data package can be downloaded from the same web page just noted.