Use of 3-Band RGB Imagery to Enhance Display of Slope, Curvature and Residual Intensity in Aeromagnetic Data

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Use of 3-Band RGB Imagery to Enhance Display of Slope, Curvature and Residual Intensity in Aeromagnetic Data

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Hibbing, Minnesota

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Summary

Since 2004, a detailed 3-band composite image of aeromagnetic intensity, slope and curvature has been used as a statewide backdrop for mineral potential evaluation work at MnDNR. The goal of the present report is to describe the basis and background behind the generation of this magnetic texture image.

The report also describes a modified, directional-derivative version of the magnetic texture image, which was developed to attenuate corrugation display effects, and the report describes a method developed to extract and maxima, minima and inflection lines from gridded aeromagnetic data. Snippets from the detailed statewide image are provided as examples of magnetic texture display and resolution.

The data package accompanying this report contains copies of the initial and directional-derivative statewide images in georeferenced TIFF format, plus a copy of the source grid of residual magnetic intensity values from which derivatives were generated, and a statewide shapefile of extracted lines of maxima, minima and inflection. A large (850 Mb) regional 3-band RGB image that includes public domain aeromagnetic data from Minnesota, Wisconsin and northern Ontario is included as separate georeferenced image file.

Background

Aeromagnetic data can be processed and displayed in a variety of ways to enhance analysis and visible display. Discussion here focuses on a visual display technique developed at MnDNR to portray the detail of Minnesota's second-generation digital aeromagnetic data within a single image, for use in routine mineral potential evaluation screening in real estate transactions involving state-owned lands.

Minnesota's second generation aeromagnetic data were originally acquired and compiled through efforts of the Minnesota Geological Survey (MGS). Chandler (1991) explains the design work and twelve year effort that resulted in this world class statewide data set. As part of that overall project, a down-sampled (25% of the original) data set was used to produce a gridded product with cell size set at approximately half of the mean flight line spacing. The gridded product cell size was 700 feet (213.36 meters), and the gridding process used a minimum curvature algorithm to calculate grid cell values.

In an effort to increase the crispness of magnetic features in imagery display during mineral potential evaluation work, the underlying full data set of ~10 million points (Hittleman and others, 1992) was processed into ESRI point shapefiles (Dahl, 1997), using computing assets considerably more powerful than were available during development of the MGS 213 meter grid a decade earlier. As part of this work, duplicate and bad data records were found and removed from the files, and flight blocks were adjusted to a common base. A number of small missing-data gaps in the point coverage were backfilled using lattice points from the 213 meter grid. The resulting shapefile data points were loaded into a TIN (Triangulated Irregular Network) format, and a 50 meter grid lattice was generated from the TIN. The initial 50 meter grid was subjected to two iterations of nearest neighbor averaging to reduce sharp edge artifacts associated with lattice points falling at TIN edges.

The 50 meter cell size was selected for the statewide grid after experimentation with cell sizes ranging from 25 to 100 meters in 12.5 meter increments. A 37.5 meter cell size might be slightly crisper in the most detailed survey blocks, but a 50 meter cell size was chosen as the optimal cell size, balancing data resolution statewide with computing power available at the time. The 50 meter cell size is ~1/8 of mean flight line spacing, which is finer than the default ¼ of line spacing used in many processing software systems. The tradeoff is that the 50 meter cell better captures along-flight line detail, but as a result some grid cells between flight lines have more interpolation and less direct connection to data points, which is less of a problem for TIN-sourced grids than for grids generated by more complex gridding algorithms. The 50 meter grid remains un-pixelated in display down to a scale of 100,000.

The magnetic texture images and extracted shapefiles described in the current report were derived from the 50 meter grid. Arguments pro and con can be applied to this methodology of grid generation, and also to spatial domain versus frequency domain processing for noise removal and derivatives generation. The 50 meter grid developed here does retain and make visible data noise due to data spikes and mis-leveling. But it also retains and makes visible fine magnetic detail that is otherwise averaged, deleted or made unrecognizable in typical efforts to produce smoothly varying surfaces for mathematical modeling.

Data Characteristics

One of the challenges in drawing out and displaying the detail in the Minnesota aeromagnetic survey data, for purposes of routine and convenient display, is that the dataset values span a range of six magnitudes. In the Minnesota data set, residual magnetic intensity values used in grid development range from lower than -10,000 nanoTeslas (nT), to greater than +30,000 nT. Within that large overall range, data variations less than 1 nT can carry geoscientific meaning. High rates of change are also present in the data set, exceeding 30,000 nT/km in some places. Displaying local fine detail within such a large values range, especially in a single statewide image, can be difficult to achieve. Shaded relief, color ramps, contours, first and second vertical derivatives, and other display techniques can be helpful for visualization purposes. But as is the case for any processing or display technique, some aspects of gridded surfaces are enhanced by these techniques, while others are degraded. In shaded relief methods, for instance, a chosen illumination direction will enhance detail that trends perpendicular to the illumination direction, but will de-emphasize detail that trends along the illumination direction. Adding vertical exaggeration to a shaded relief display can enhance fine relief detail, but will also cause the same types of detail to be lost in exaggerated shadows of higher amplitude features. The multi-band display methodology described in this report arose from an effort to enhance very subtle magnetic variations along the south flank of the Soudan iron formation within the Vermilion greenstone belt of Minnesota, anomalies that might be useful in informing volcanic-hosted massive sulfide or orogenic gold mineral potential interpretations. The high amplitude of the magnetic anomaly associated with the iron formation was causing shadow issues and loss of detail in adjacent anomalies, even when display was approached from several different illumination angles and vertical exaggeration settings. The presence of multiple magnetic anomalies having varying orientation was causing some features to be lost in display regardless of chosen illumination direction.

Using many images to display detailed aeromagnetic data in an environment such as land management mineral potential analysis can become cumbersome, because such analysis typically involves many other natural resource layers, not just an array of geophysical displays. The display method described here for aeromagnetic data was partly developed as a means to reduce the amount of image hopping needed to visualize a magnetic surface during analysis for land management decisions. Generating and viewing several aeromagnetic images during analysis to understand variation in amplitude, orientation, first and second derivative characteristics, and other aspects of magnetic anomalies was not uncommon. From an analyst's perspective, the more content that can be packed into and shared in a single geophysical image the better.

Another challenge in developing aeromagnetic data sets is that they tend to be anisotropic, meaning that the number of measurements collected per kilometer along flight lines is typically much greater than the spacing between flight lines. It can be difficult to draw into a gridded surface the full resolution of data available along the high-density data direction, without losing continuity across the low-density data direction. In the Minnesota data set the anisotropy varies from flight block to flight block, but can generally be considered to be on the order of 8:1, that is, eight times higher data density along the flight line direction than across the flight line direction. In some places the anisotropy reaches 10:1. Generation of grid lattice points from a TIN surface having triangles with 8:1 length to width ratio works out better than might be expected, as the lattice points mostly intersect the widest, most representative parts of TIN triangles. Regardless of gridding method used, features oriented greater than 45 degrees to flight line orientation can be difficult to connect during gridding efforts, leading to "bullseye" anomalies in the gridded result. Semi-automated strike-oriented gridding methods can partly overcome these bullseye tendencies, as demonstrated in a pilot project by Scott Hogg and Associates (Dahl, 2017), allowing more data and finer grid cell size to be used, but those techniques were not yet well-developed at the time of this imagery work.

Handling of anisotropic aeromagnetic data has been approached by geophysicists in several ways. Historically, due to processing and display limitations of hardware and software, aeromagnetic data interpreters fell into two camps. The "profilers" would tend to evaluate the full amount of data on each flight line profile and then transfer the results of those analyses onto a map. The "gridders" would tend to downsample the along-line data in order to yield a more isotropic overall data set, and then generate gridded surfaces amenable to rapid modeling analysis using grid functions. Gridders would also accept contrast-stretched image displays of data as a visual enhancement technique.

The profile and grid approaches are both valid. In the past, the techniques were complicated enough to require some specialization in one or the other approach in order to achieve technique proficiency. One objective in this work was to place profile and grid data together for common use by both profilers and gridders. More recently, processing and display technologies have advanced to the point where these different approaches are no longer considered specialty niches, but are viewed as complementary tools within a single software package.

Since development of the 50 meter grid and related imagery, Chandler (2007) has developed a 100 meter statewide grid, using the shapefiles developed by Dahl as a basis, recovering some of the flight line gap data, and incorporating some additional leveling in in the process. The 100 meter grid developed by Chandler is designed to support mathematical modeling. The 50 meter grid developed by Dahl is designed to make visible the full detail of the data, both noise and geologic signal, as a visualization and textural reference display. These are complementary products. Likewise, lines of maxima, minima and inflection extracted from the 50 meter grid are intended to serve as an aid in tracing magnetic edges and discontinuities during geologic interpretation.

3-Band RGB Aeromagnetic Imagery

The 3-band RGB imagery described here combines the display of amplitude (residual magnetic intensity), slope, and profile curvature into a single image. A ghosting of flight-line parallel shaded relief is included to help distinguish surface highs from surface lows. Development of the imagery used ESRI GIS software tools (at the time ArcInfo 7.x software and AML programming language). The processing script used the topographic analysis tools Slope, Aspect, and Profile Curvature developed by Zevenbergen and Thorne (1987), and as implemented in ArcInfo's Grid extension, applied to the 50 meter grid, in order to generate slope, aspect and profile curvature grids. The script then carried out contrast stretches of these grids using hard coded variables, and spliced a ghosting of shaded relief into the image. The resulting red (slope), green (curvature) and blue (amplitude) grids were merged into a single 3-band RGB GeoTIFF georeferenced image. Color ramp directions for slope, curvature and amplitude components in the script were chosen so that high amplitude positive magnetic anomalies having high slope and high convex curvature, such as the positive anomaly of the Soudan iron formation, would display white (RGB=255,255,255), and highly negative anomalies would display dark or black (RGB=0,0,0). The script used was finalized as follows:

```
/* March 2, 2004
/* D. Dahl, MnDNR Lands and Minerals
/* imagestrshd.aml
/* makes a three band rgb tiff image of slope, curvature, intensity for the input grid, and merges
/* the result with a grayscale shaded relief grid.

/* get the name of the input grid
/* &sv gridnam = [response 'name of ingrid for surface texture image']
/* make the profile and slope grids
grid
mapextent m593
/* scurv = curvature(%gridnam%,sprof,#,sslop,#)
/* kill scurv

/* make the red stretch
&describe m593slop
&sv hiend = %GRD$MEAN% + (1 * %GRD$STDV%)
&sv loend = %GRD$MEAN% - ( 1 * %GRD$STDV%)
strclip = con(m593slop > %hiend%, %hiend%, m593slop < %loend%, %loend%, m593slop)
/* kill sslop
redstr2 = slice(strclip,eqinterval,254,0)
kill strclip
redstr = con(isnull(redstr2),255,redstr2)
kill redstr2

/* make the green stretch
&describe m593p50
&sv hiend = %GRD$MEAN% + (2 * %GRD$STDV%)
&sv loend = %GRD$MEAN% - (2 * %GRD$STDV%)
strclip = con(m593p50 > %hiend%, %hiend%, m593p50 < %loend%, %loend%, m593p50)
```

```
/* kill sprof
/* strclip = strclip2 * (-1)
/* kill strclip2
grnstr2 = slice(strclip,eqinterval,255,0)
kill strclip
grnstr = con(isnull(grnstr2),255,grnstr2)
kill grnstr2
&type '....finished making green grid....'

/* make the blue stretch
&describe m593
&sv hiend = %GRD$MEAN% + (1 * %GRD$STDV%)
&sv loend = %GRD$MEAN% - ( 1 * %GRD$STDV%)
strclip = con(m593 > %hiend%, %hiend%, m593 < %loend%, %loend%, m593)
blustr2 = slice(strclip,eqinterval,255,0)
kill strclip
blustr = con(isnull(blustr2),255,blustr2)
kill blustr2

/* convert the r-g-b grids to h-s-v
strhue = rgb2hue(redstr, grnstr, blustr)
strsat = rgb2sat(redstr, grnstr, blustr)
strval2 = rgb2val(redstr, grnstr, blustr)
kill redstr
kill grnstr
kill blustr

/* make the shaded relief grayscale grid
/* setwindow %gridnam%
/* setcell %gridnam%
/* mapextent %gridnam%
/* shdval2 = hillshade(%gridnam%,0,45,shade,20)
shdval = slice(m593shdn,eqinterval,100,0)
/* kill shdval2

/* merge the grayscale grids
strval = (0.40 * shdval) + (0.60 * strval2)
kill shdval
kill strval2

/* convert from h-s-v back to r-g-b grids
redstr2 = hsv2red(strhue, strsat, strval)
grnstr2 = hsv2green(strhue, strsat, strval)
blustr2 = hsv2blue(strhue, strsat, strval)
kill strhue
kill strsat
kill strval
redstr = con(isnull(redstr2),255,redstr2)
grnstr = con(isnull(grnstr2),255,grnstr2)
blustr = con(isnull(blustr2),255,blustr2)
kill redstr2
kill grnstr2
kill blustr2

/* make the stack, quit Grid, make the 3-band image, and do some cleanup
makestack istack list redstr grnstr blustr
quit
gridimage istack none am593.tif tiff compression
kill redstr
kill blustr
kill grnstr
kill istack
&type 'done with processing'
```

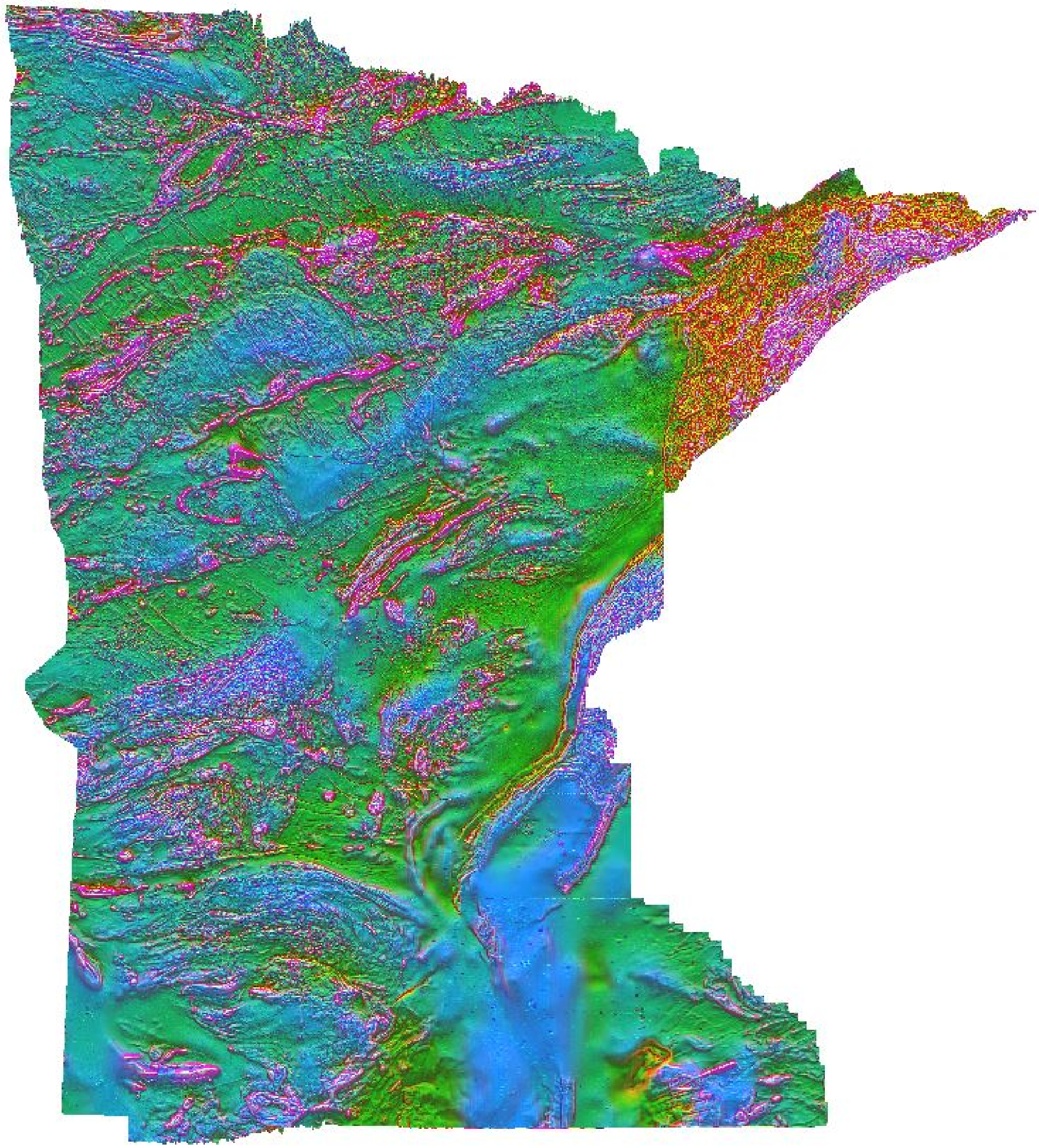
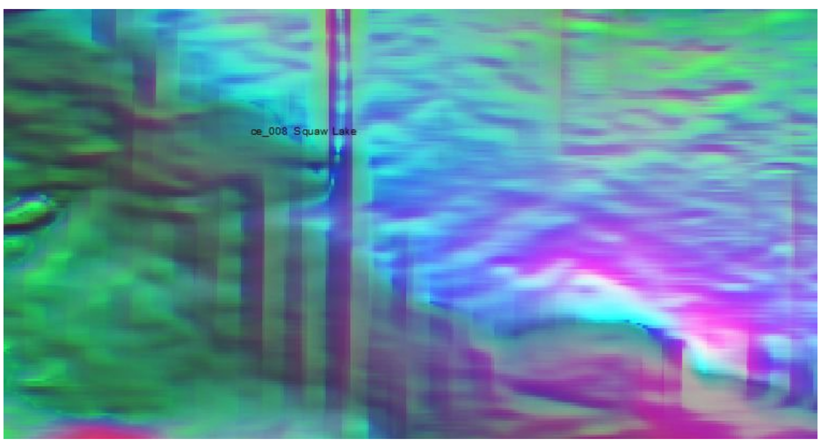


Figure 1. Statewide view of 3-band RGB image of 2nd generation aeromagnetic data set of Minnesota at ~1:3,300,000 scale. Areas of green are regionally magnetic concave, areas of blue are regionally magnetic convex. Brighter red, yellow and white areas are local anomalies superimposed on the regionally concave and convex surfaces. See the data package for the entire image at full resolution at 100,000 scale.

Modified Directional-Derivative 3-Band RGB Imagery

In detail, the 3-band RGB image is very good at detecting and displaying subtle variation in the gridded magnetic surface. The top image of the pair in Figure 2 is a snippet from the statewide image. The vertical striping in the image corresponds to small mis-leveling errors in the flight line data. Each vertical stripe corresponds to a flight line, and the 3-band image is doing a very good job of detecting those small line-to-line variations. This corrugation effect occurs in the X component of the grid, and the slope and curvature bands of the image are enhancing that variation. To attenuate the corrugation, the Zevenbergen and Thorne equations can be manually recalculated using map algebra, to zero out the X component in the equations, to yield Y-derivative results (see Appendix A). Since the Y-derivatives are calculated along the flight line direction, they ignore the X component of the surface that is causing the across line corrugation. The result is shown in the bottom snippet of the pair in Figure 2. Note that the corrugation has not been removed from the original source grid, but the cross line corrugation effect has been minimized in display. Removing the X component of the surface from slope and curvature calculations does change the appearance of the east and west ends of smaller anomalies, and it is beneficial to use the original image and Y-derivative image together along with the original flight line data points.



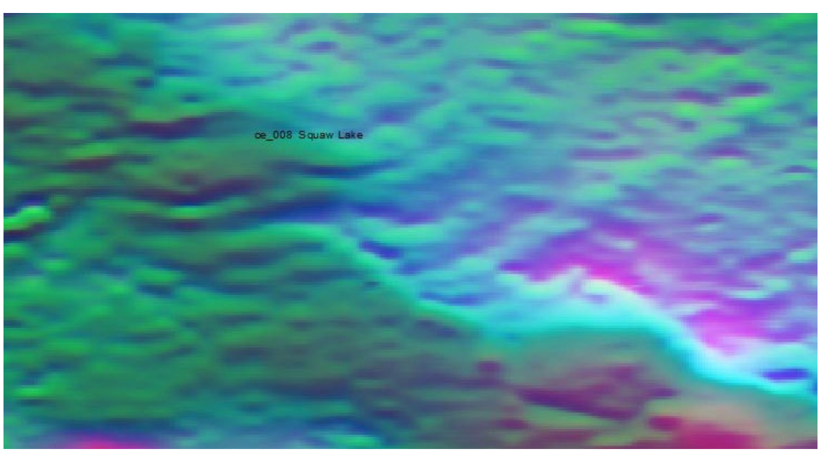
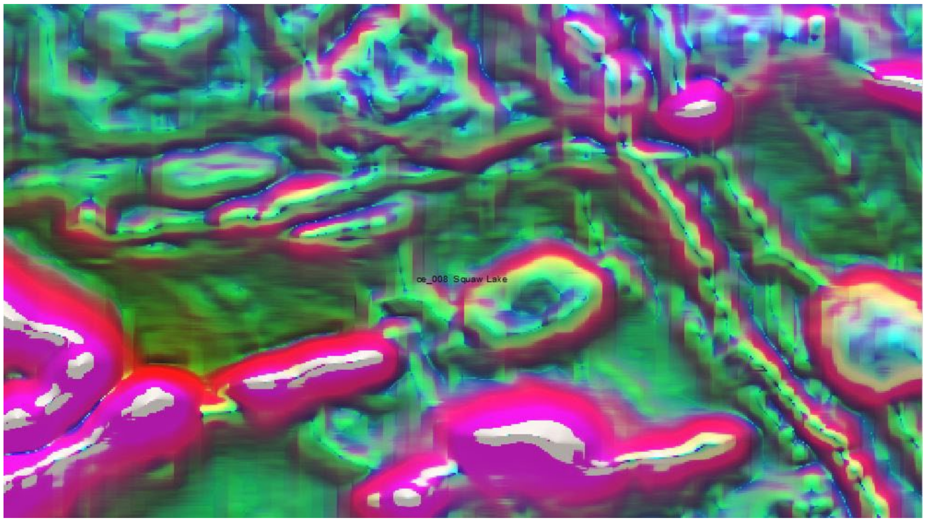


Figure 2. Top image - vertical corrugation due to flight line mis-leveling. Bottom image - same display area following corrugation attenuation using y-derivative slope and curvature grids in image generation.

The pair of images in Figure 3 are from a location near Ball Club west of Grand Rapids, MN. The lower, Y-derivative image of the pair cleans up some corrugation artifacts that might otherwise be interpreted as structural breaks, particularly in the linear white anomalies in the south half of the image. Note that the quality of the circular intrusion anomaly on the east side of the image becomes less distinct in the lower image, because the X component of the western edge of the anomaly is missing in the Y-derivative display. What stands out though in the lower image is the linear anomaly that runs across the center of the image, which forks near the center of the image. In the upper image of the pair, that linear anomaly is essentially invisible, due to corrugation. The linear anomaly being resolved in the lower image is associated with a railroad and utility corridor along highway 2. A buried pipeline in that corridor branches to the west near the center of the image. Remarkably, the negative and positive portions of the dipole anomalies associated with these features are less than 1 nT each, yet they show up clearly within an image having a values range of 3,500 nT. The anomaly at the tip of the yellow arrow in the lower image is 1.35 nT peak-to-trough. For reference, the image area in Figure 3 is 25 km across.



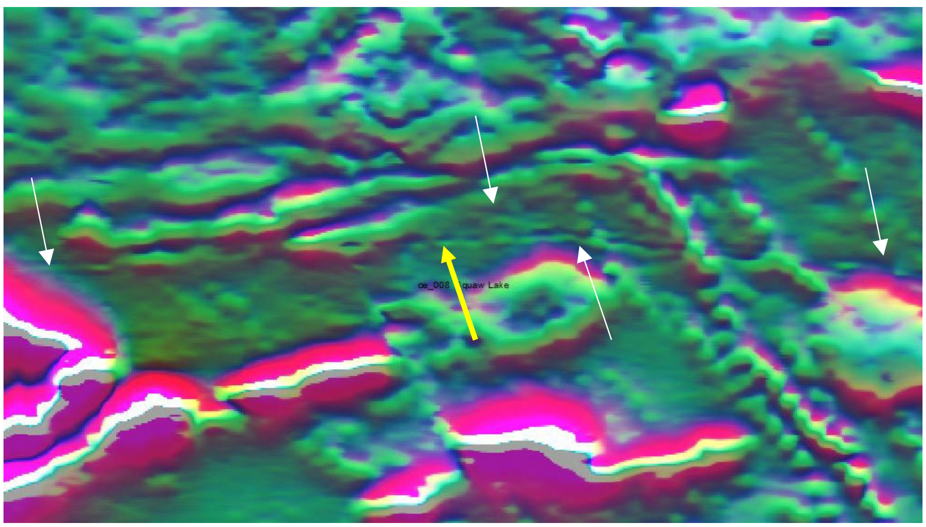


Figure 3. Corrugation attenuation in the Ball Club area west of Grand Rapids, Mn. Top snippet from original 3-band RGB image. Lower snippet from y-derivative modified image. Arrows point to utility anomalies resolved in the display.

The statewide 3-band Y-derivative RGB image is shown in in Figure 4.

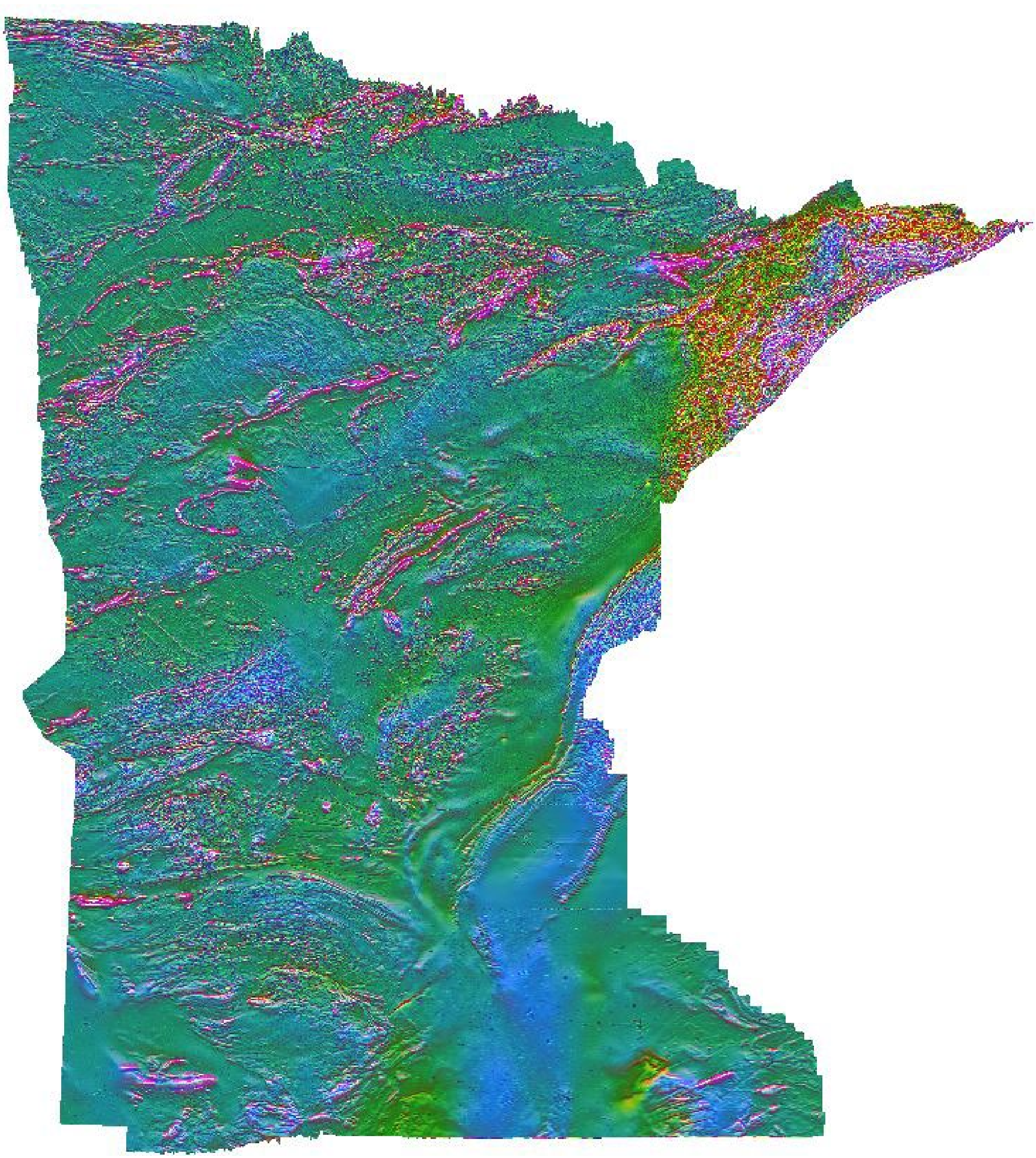


Figure 4. Statewide view of 3-band RGB y-derivative image of 2nd generation aeromagnetic data set of Minnesota at ~1:3,300,000 scale. Description as noted in figure 1. See the data package for the full resolution of the image at 1:100,000 scale.

Figure 5 illustrates the extent of a 3-band RGB image constructed from public domain aeromagnetic data of Minnesota, Wisconsin and northern Ontario.

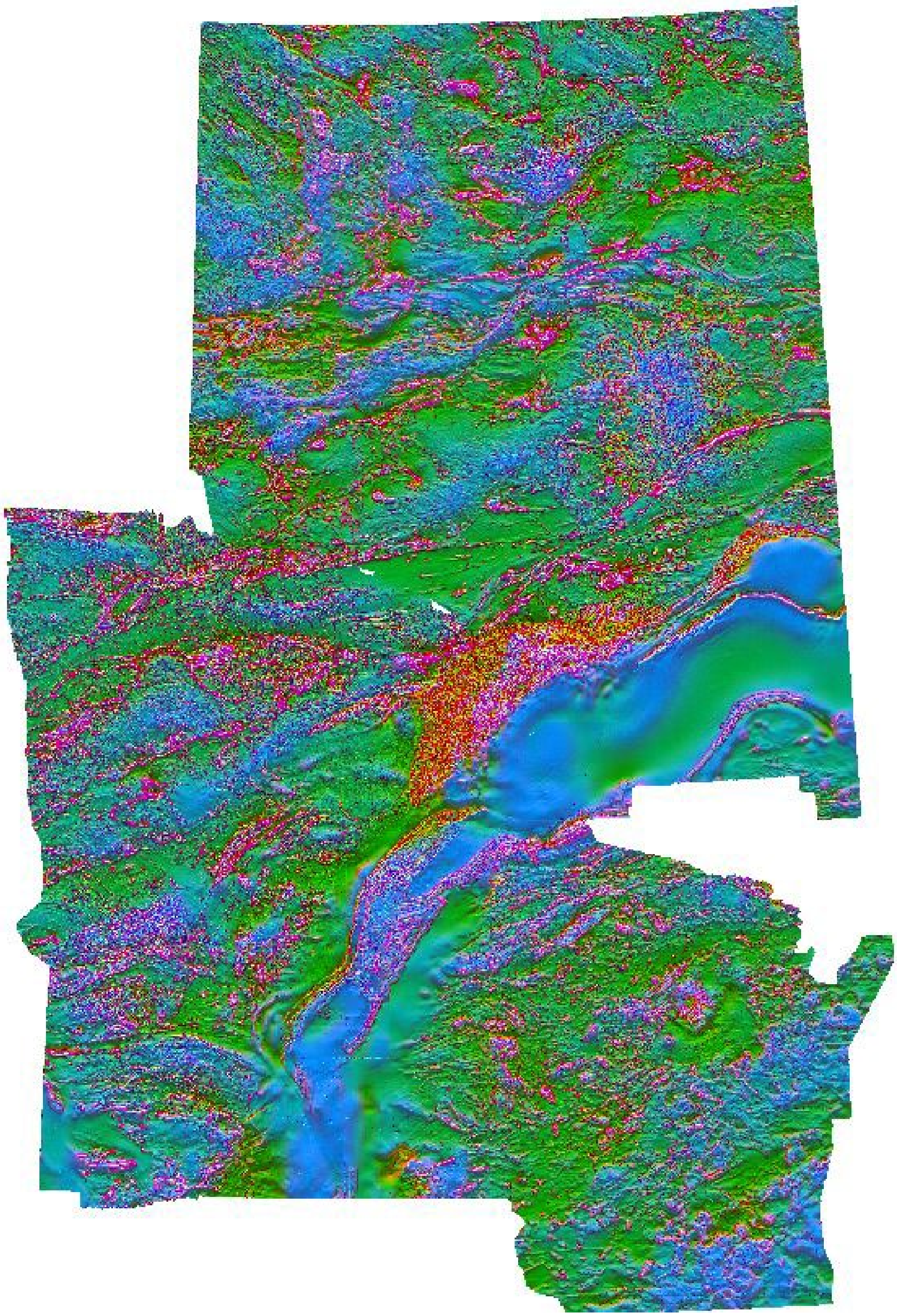


Figure 5. Regional 3-band RGB image showing continuity of regional scale features across public domain aeromagnetic data areas of Minnesota, Wisconsin and northern Ontario. See data package for detail and full resolution of image.

Lines of Maxima, Minima and Inflection

To extract lines of maxima, minima and inflection from the 50 meter grid, a series of focal, classification and zonal functions were applied, followed by a zone-to-polygon conversion. One focal (neighborhood) function developed by Zevenbergen and Thorne calculates an Aspect value for each cell in a grid. Aspect is the facing direction of the steepest downhill slope away from the cell being calculated, and is calculated using a 3 x 3 neighborhood of cells that includes the cell of interest. Aspect is reported as compass direction, zero to 360. Calculation of Aspect on a grid will result in values that point away from maxima, toward minima on a surface. Aspect calculation on a derived Slope grid will yield values that point toward and away from inflections on the surface as well maxima and minima. In the current work, Aspect was calculated on the Y-derivative Slope grid. Values having a northward-pointing component (270 to 360 degrees, and 0 to 90 degrees) were reclassified to 0 (north). Aspect values having a southward-pointing component (90 to 270 degrees) were reclassified to a value of 180 (south). A zonal function was used to aggregate cells classified as 180, and cells classified as 0. These zonal areas were then converted to polygons. The polygon boundaries trace the maxima, minima, and inflection lines in the Y-derivative grid. East-west trending lines are well defined. North-south trending lines need some interpretation, due to factors listed earlier – anisotropy in the X data (cross flight line) direction and corrugation due to unresolved mis-leveling in the dataset. Interpreting fault versus fold geology where aeromagnetic data show discontinuity can be subjective when working with smaller, thinner anomaly features, so the need for subjective interpretation of the discontinuity components of these maxima, minima and inflection lines is not unexpected.

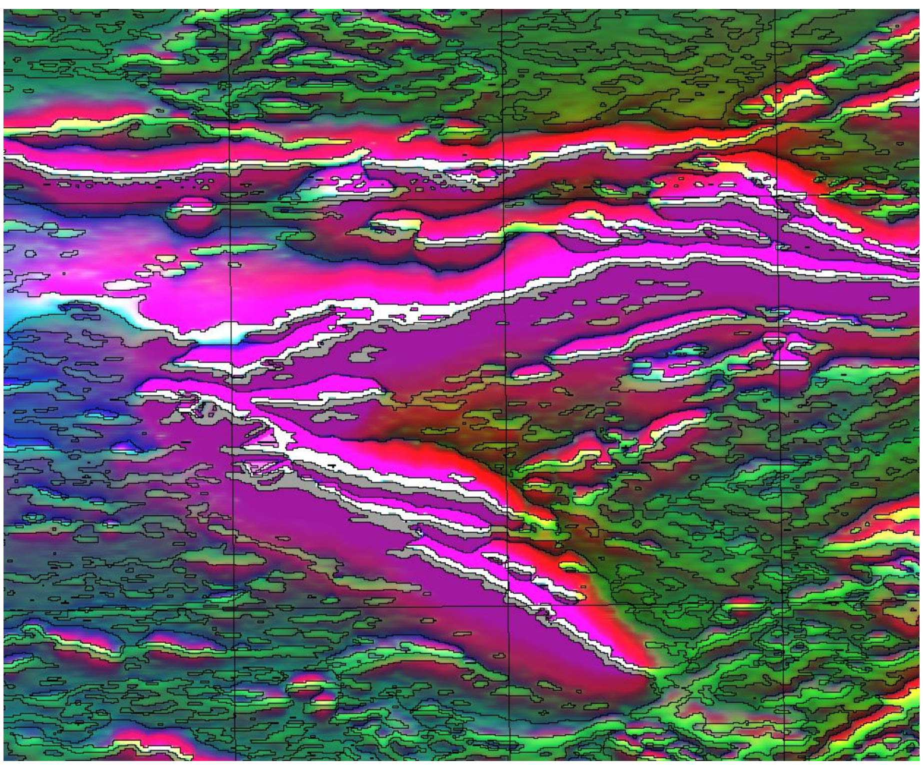


Figure 6. Maxima, minima and inflection lines extracted from the aspect of the y-derivative slope of the 50 meter grid. 3-band RGB y-derivative image in backdrop, and vector maxima, minima and inflection lines as black linework.

Figure 6 illustrates lines of maxima, minima and inflection superimposed on the Y-derivative 3-band RGB image in the Soudan iron formation area. In the figure one can see that vector lines separate convex from concave portions of the grid (inflection lines), and trace the peaks of the highly magnetic iron formation anomalies. Minima lines trace the axis of lows between anomalies. The zone-to-polygon conversion produces some very large polygons having large numbers of vertices, so in this work the zonal polygons are unioned with the 7.5 minute topographic map tile polygon layer, in order to cut otherwise unwieldy zonal polygons into manageable features.

Figure 7 shows an overlay of bedrock geology map S-21 iron formation units (in red) against the lines extracted from the 50 meter grid, for the same area as in Figure 6. There is opportunity to extend, for mineral potential evaluation purposes, some iron formation units based on continuation of inflection lines beyond currently drawn boundaries. Opportunity also exists to realign/reinterpret the orientation of some features in the northern half of the image. Extracted lines do not substitute for good geological interpretation to distinguish between useful edges versus edges-too-noisy-to-interpret. The extracted lines do show areas of coherent traceable edge that may be helpful in interpreting the gridded aeromagnetic data.

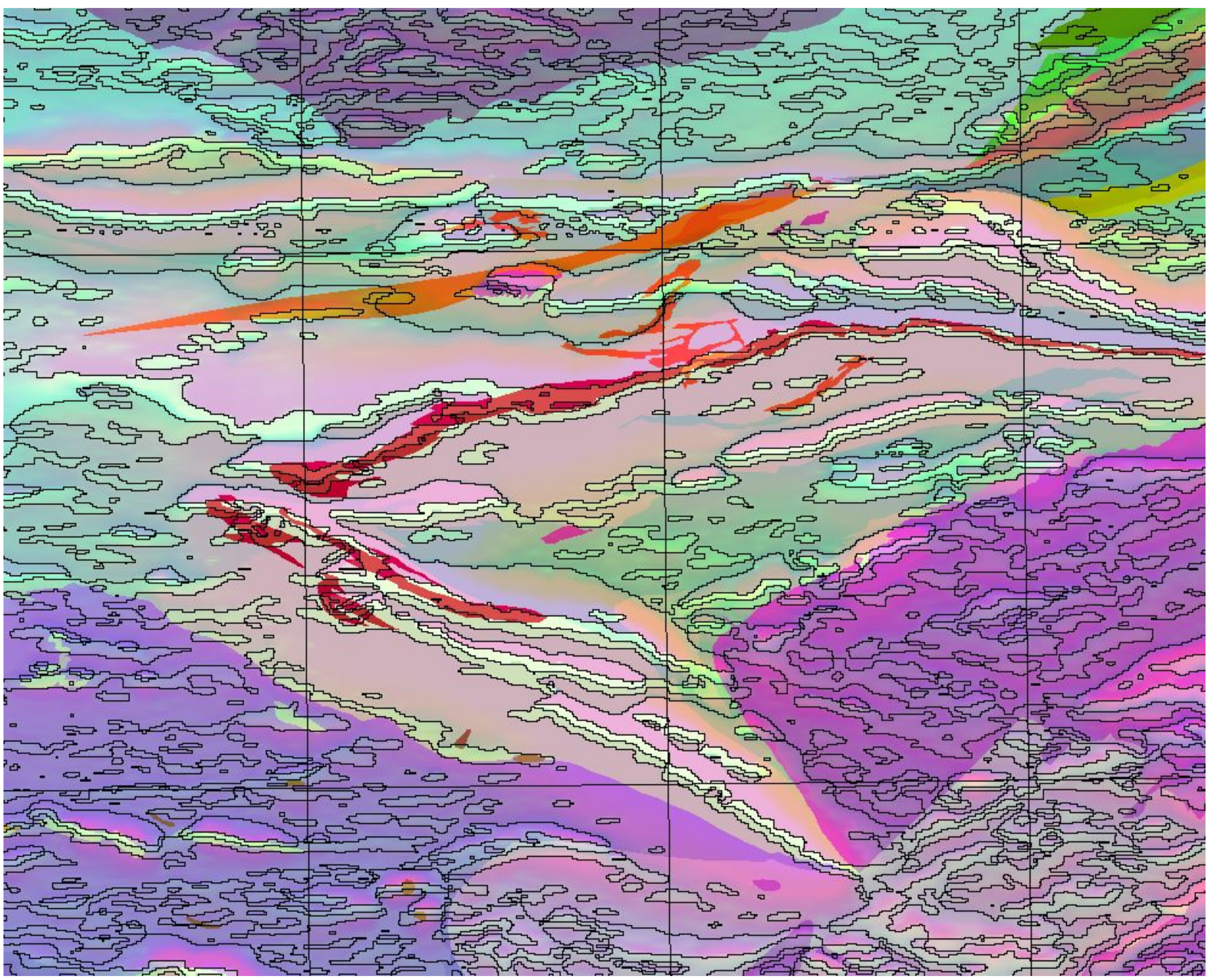


Figure 7. Iron formation and geologic interpretations from Minnesota Geological Survey Bedrock Map S-21 superimposed on extracted lines and 3-band RGB image.

Summary and Recommendations

The use of more data, alternate gridding and derivatives methods, and alternative image display methods for Minnesota's 2nd generation aeromagnetic data set allow for fine detail to be drawn out for display purposes. These 3-band RGB aeromagnetic texture images show additional detail of geologic signal and data noise, allowing more confident interpretation of processing results and as an aid to interpretation. Extracts of maxima, minima and inflection lines may serve as an aid when tracing geologic interpretations.

The AML script outlined earlier in the report could be translated to a Python script to enable a more interactive dialog box format for generating the 3-band display. Extent of stretch and other hard coded variables could be handled as sliders to more easily optimize the visual result.

As for any display of gridded data, it is prudent to overlay the source data, in this case the flight line point data, so that limitations of the original data sources can be viewed directly against the gridded result. In reality, aeromagnetic flight line traces are not straight lines acquired at precise intervals, and it is helpful to see how wander in the flight line traces, both laterally and vertically, translates into gridded results on formational and structural anomaly features.

Beyond keeping source data layers close at hand for overlay during analysis and interpretation, users of these image products will wish to overlay them on conventional 1st and 2nd vertical derivative images, to see how the maxima, minima and inflection lines of the Zevenbergen and Thorne spatial-domain horizontal derivatives compare to frequency domain vertical derivatives and reduced-to-pole grids.

The detail in the 3-band RGB images indicate that the drumlins in the Wadena drumlin field also show up as anomalies in the 3-band imagery, particularly in the Y-derivative image, in the area overlying the Nimrod Basin. There may be insight to be gleaned there that may apply to unraveling the semi-dendritic pattern of magnetic anomaly seen in the Animikie Basin area. The Animikie Basin anomaly pattern contains endmembers that in some cases are clearly intrusive features, some that are glacial features, some that may correspond to leveling issues (anomalies at lakes), some related to underlying bedrock topography structures, and many that at this point can be visualized but not well interpreted. Better analysis of the Nimrod Basin drumlin anomalies may help to better classify glacial feature anomalies in the Animikie Basin.

The detail in the 3-band RGB Y-derivative image greatly draws out the expression of the transpressional structural framework that underlies the Mesabi iron range. The correspondence of natural ore mine locations and shape to the structural anomalies detailed in the imagery is striking, indicating that reactivation of the earlier transpressional structures plays a significant role in localizing structural preparation of the Biwabik iron formation, followed by weathering in these structural zones to produce naturally enriched iron ores. Additional exploration along these transpressional structural features may result in discovery of additional natural ore resources. Visualization of the larger transpressive structural system may also help in understanding the distribution of structural features that influence the distribution of gold mineralization in the Virginia Horn area, the Long Lake fault area, and the Bear River structure area.

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Appendix A: GIS tools and Equations

The ESRI suite of Geographic Information System software products includes a number of focal and zonal functions for processing and evaluating gridded raster surfaces. One suite of focal functions is based on work by Zevenbergen and Thorne (1987). Their approach uses a point and its eight surrounding grid neighbors, (essentially a 3 x 3 matrix), in conjunction with a partial quartic equation, to generate a curved mathematical surface that passes exactly through the nine points of the neighborhood. They calculate topographic indices for the center point of this neighborhood, including elevation, aspect (compass direction of steepest slope away from the center point of the neighborhood), and slope, profile curvature, planform curvature, and overall curvature. Profile curvature is calculated in the direction of steepest slope. Planform curvature is calculated transverse to steepest slope. The slope of the neighborhood surface is the first derivative. Curvature, a measure of how concave or convex the neighborhood surface is, is called the second derivative of the surface.

Zevenbergen and Thorne's equation 2 is used to derive topographic indices for a gridded surface.

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I \qquad \text{[Zevenbergen and Thorne eq. 2]}$$

They then determine the nine parameters A through I from the nine elevations of the of the 3 x 3 matrix, using Lagrange polynomials. Their equations 3 through 11 are:

$$A = [(Z_1 + Z_3 + Z_7 + Z_9)/4 – (Z_2 + Z_4 + Z_6 + Z_8)/2 + Z_5]/L^4$$

$$B = [(Z_1 + Z_3 - Z_7 - Z_9) / 4 – (Z_2 - Z_8) / 2] / L^3$$

$$C = [(- Z_1 + Z_3 – Z_7 + Z_9) / 4 + (Z_4 – Z_6) / 2] / L^3$$

$$D = [(Z_4 + Z_6)/2 – Z_5] / L^2$$

$$E = [(Z_2 + Z_8)/2 – Z_5] / L^2$$

$$F = (- Z_1 + Z_3 + Z_7 - Z_9) / 4L^2$$

$$G = (- Z_4 + Z_6) / 2L$$

$$H = (Z_2 – Z_8) / 2L$$

$$I = Z_5$$

The nine elevations Z_1 to Z_9 in the parameter equations correspond to the nine elevations in the 3 x 3 neighborhood, numbered as follows:

$$\begin{matrix} Z_1 & Z_2 & Z_3 \\ Z_4 & Z_5 & Z_6 \\ Z_7 & Z_8 & Z_9 \end{matrix}$$

They then derive topographic indices by differentiating their equation 2 and solving that equation for the central point of the matrix ($x = y = 0$). Slope (first derivative of Z) is calculated in the direction of aspect:

$$\text{Slope} = -(G^2 + H^2)^{1/2} \qquad \text{[Zevenbergen and Thorne eq. 13]}$$

Aspect (maximum slope direction) is derived from the slope equation to yield:

$$\text{Aspect} = \arctan(-H/-G) \qquad \text{[Zevenbergen and Thorne eq. 15]}$$

The curvature (second derivative of Z), for any direction ϕ, is calculated as:

$$\text{Curvature} = 2(D\cos^2\phi + E\sin^2\phi + F\cos\phi\sin\phi) \qquad \text{[Zevenbergen and Thorne eq. 16]}$$

Profile curvature (in the direction of maximum slope) is calculated as:

$$\text{Profile Curvature} = -2\,(DG^2 + EH^2 + FGH)\,/\,(G^2 + H^2) \qquad \text{[Zevenbergen and Thorne eq. 17]}$$

Planform curvature (transverse to the direction of maximum slope) is calculated as:

$$\text{Planform Curvature} = 2\,(DH^2 + EG^2 - FGH)\,/\,(G^2 + H^2) \qquad \text{[Zevenbergen and Thorne eq. 18]}$$

These topographic indices for slope, aspect, curvature, profile curvature and planform curvature are implemented for analysis of elevation grids in ArcGIS spatial analyst software. These neighborhood functions can also be applied for analysis of other gridded surfaces such as aeromagnetic data. Parameters A through I can also be calculated separately as grids using the raster algebra functions of ArcGIS Spatial Analyst extension, to derive directional topographic equations, such as zeroing out the x-directional parameters to yield y-directional (along flight line) derivatives, or zeroing out y-directional parameter to yield x-directional (across flight line) derivatives.

Appendix B: Data Package Files

Digital files to accompany project 408: Use of 3-Band RGB Imagery to Enhance Display of Slope, Curvature and Residual Intensity in Aeromagnetic Data. All GIS data is cast in UTM Zone 15 Projection, NAD83 Datum with X and Y units in meters.

AM593.zip	contains statewide 3-band RGB georef TIFF image at 50m cell size
ASUPER5316.zip	contains modified y-derivative version of 3-band RGB TIFF image
AONMINWIMAG.zip	contains 3-band RGB image for Minnesota, Wisconsin, northern Ontario
M53180UUPOLY.zip	contains polygon shapefile whose boundaries are maxima, minima and inflection lines
M531.zip	contains statewide 50 meter grid in ESRI Grid format
MAG_PT_SHAPES.zip	contains source point shapefiles of aeromagnetic survey data

Appendix C: Metadata on Aeromagnetic Data Point Shapefiles

Notes: Minnesota Aeromagnetic Data

Conversion of CD-based ascii Files to Arc/Info Point Coverages and Arc/Info Grids

D. Dahl
MnDNR-Minerals
January 29, 1997

Background

In 1992, the Minnesota Geological Survey, in cooperation with NOAA's National Geophysical Data Center, released a two cd-rom set of aeromagnetic information covering the state of Minnesota.

The purpose of this document is to describe the procedures used to extract the binary data files from the CD's, the steps taken to convert ascii versions of the extracted files into Arc/Info point coverages and grids (having common datum, projection, and coordinate systems), and the steps taken to verify those conversions.

Three sets of data were extracted from the CD's and processed during this conversion work.

> The first data set is the Minnesota Aeromagnetic Data collected over a twelve year period (1979-1991) by the the Minnesota Geological Survey through appropriations from Minnesota's Legislative Commission on Natural Resources. These data represent the most comprehensive regional aeromagnetic survey available in the state, having ~50 meter point spacing, quarter mile (~400m) line spacing, two mile (~3200m) tie line spacing, and 500 foot terrain clearance. The data are contained in 60 files. Three additional files contain lower resolution data for Lake Superior (Geol. Surv. Canada), Lake of the Woods (Geol. Surv. Canada), and northwestern Wisconsin (USGS), and six other files covering the southwestern Minnesota area were donated to MGS by US Steel Corp. Data for the metropolitan Minneapolis/St. Paul area were digitized from existing U.S. Geologic Survey maps, but was not incorporated as point data for the CD's.
>
> The second data set consists of several grids that were derived from the original point data of the Minnesota set. The primary grids were set up based on a 700 foot (~213m) cell size.
>
> The third data set contains the results of an earlier aeromagnetic survey conducted by the federal government as part of the National Uranium Resource Evaluation (NURE) program. The NURE data are in 19 files. Visual inspection of these files suggests that the NURE surveys were conducted with point spacing of about 75 meters, ~3 mile (~5000m) flight line spacing, and ~20 mile (~30000m) tie line spacing.

375 NT difference

In total, the two CD set contains over 597,000 flight line miles in 88 files which include 14.7 million records having a total of approximately 150 million attribute values.

Equipment and Software

The flight line data files were extracted from the cd-rom set and converted to ascii format using the Minnesota Aeromagnetic Data CD-ROM Access Software, which was provided on 5 1/4" diskettes as part of the data publication. Ascii files of gridded data were copied directly from the cd without using the access software. Flight line files were given names similar to those shown on the menu system of the access software.

The data files were then transferred from the Hibbing office network server by ftp to a Sun Microsystems Sparcstation20 containing 2x75mhz sparc processors, 64 Mb RAM and 20 Gb disk capacity.

Files were subsequently processed using Arc/Info version 7.0.4, Arc/Info's AML programming language, and unix vi and solaris text editors. The unix operating system was Solaris, version 2.4.

At a rate of approximately 50,000 records per hour, the bulk of the record processing and coverage generation required a little over 300 cpu hours. An additional 30 hours of cpu time were required to run frequencies and statistics on attribute values and to generate verification plots. Approximately 60 hours of pc time were used in extracting the files from the CD's and transferring files to the unix workstation. Most of the processing and formatting work was done over the course of an approximately ten week period.

The completed Arc/Info point coverages and grids take up about 2.2 Gb of disk space on one of the Hibbing drives.

Purpose

The primary purpose in extracting and processing the data into Arc/Info format was in response to controversy over whether to use flight line data or gridded data for mineral potential evaluations. By placing both of the data sets into a common, accessible, comparable, and easily visualized format, the author of this note intends to make the advantages of both types of data available for such types of evaluation.

Layout of these notes

The flight line data files are divided into directories by area of the state, corresponding to the menu layout of the access software. There are uniform file formats and attribute code structures within each directory. Exceptions are noted. Processing notes for each group of files are listed on the following pages. Refer to the caveats file on the cd-rom set (and also attached here as an appendix) for additional details on data aquisition. Also refer to the second appendix, also copied from the cd-rom set which gives definitions and units to the attribute items.

- Lite Metadata - - Get Data - - View Attribute Table - - View Sample -

Minnesota Geological Survey

Minnesota Aeromagnetic Data

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metadata created using Minnesota Geographic Metadata Guidelines .

Go to Section:

Section 1	*Identification Information - - - - - - top*
Originator	Minnesota Geological Survey
Title	Minnesota Aeromagnetic Data
System Name	aeromagx
Abstract	Statewide aeromagnetic flightline data in Arcview shapefile format. 14 million points processed into sixty-nine shape files. Data extracted from the NOAA-NGDC 2-CDROM set of binary flight line tables. North-south flight lines spaced 1/4 mile apart. Sample points along flight lines spaced 50-75 meters apart. 125 meter mean terrain clearance. Data were collected over a 12 year period through contracts administered by Minnesota Geological Survey.
Purpose	Data were collected to provide a geophysical framework for mapping Minnesota's bedrock geology and to provide a basis for establishing characteristics of Minnesota's mineral endowment
Time Period of Content Date	1991
Currentness Reference	State was systematically flown during a 12 year period (six funding cycles to complete the statewide coverage). Data collection began in 1979 and was completed in 1991.
Progress	Complete
Maintenance and Update Frequency	None Planned
Spatial Extent of Data	Statewide except metropolitan Twin Cities area
Bounding Coordinates	E = -89 W = -97.5 N = 49.5

	S = 43
Place Keywords	Minnesota
Theme Keywords	Aeromagnetic, Magnetic, Airborne Geophysics
Theme Keyword Thesaurus	None
Access Constraints	None
Use Constraints	Please credit the sources that led to these data sets: Minnesota Aeromagnetic Data were aquired by the Minnesota Geological Survey through funding by Minnesota's Legislative Commission on Natural Resources. Data were originally published by the National Geophysical Data Center (NOAA-NGDC). Processing of the data to produce GIS point coverage was done by MnDNR-Lands and Minerals.
Contact Person Information	Dave Dahl, GIS Specialist/Geologist DNR- Division of Lands and Minerals 1525 Third Avenue East Hibbing, MN 55155 Phone: (218) 262-7322 FAX: (218) 262-7328 E-mail: dave.dahl@dnr.state.mn.us
Browse Graphic File Name	aeromagx_sam.gif
Browse Graphic File Description	
Associated Data Sets	Gridded aeromagnetic data, 700 foot (213 meter) cell size, statewide; and grids/images derived from the original grid.
Section 2	*Data Quality Information - - - - - - top*
Attribute Accuracy	Not assessed
Logical Consistency	Data are topologically correct using Arc/Info 7.0.4
Completeness	
Horizontal Positional Accuracy	Varies by contractor.
Vertical Positional Accuracy	Not Applicable
Lineage	Data collected by several airborne geophysics contractors over a 12 year period (1979-1991) for the Minnesota Geological Survey through appropriations from Minnesota's Legislative Commission on Natural Resources. These data represent the most comprehensive regional aeromagnetic survey available for the state, having ~50meter point spacing along flight lines, 1/4 mile (~400m) flight line spacing, 2 mile (~3200m) tie line spacing, and 500 foot (~150m) terrain clearance. The data are contained in 60 files. Three additional files contain lower resolution data for Lake Superior and Lake of the Woods (Geological Survey of Canada) and northwestern Wisconsin (U.S. Geological Survey). Six other files covering southwerstern Minnesota were donated to MGS by U.S. Steel Corp. Data for the metropolitan Minneapolis/St. Paul area were digitized from existing U.S.

	Geological Survey maps but were not included in the original data release and are not included with this data layer. MGS published the data through the National Geophysical Data Center in Boulder, Colorado, which is part of the National Oceanic and Atmospheric Administration (NOAA) branch of the U.S. Department of Commerce. The 2 CDROM set of binary files is titled "Minnesota Aeromagnetic Data" , and "Aeromagnetics-Earth System Data: Minnesota Region". NGDC developed an extraction software for unloading the binary files off of the CD set and onto a user's hard drive in an ASCII format. MnDNR-Lands and Minerals Extracted all of the data from the NGDC 2 CDROM set, processed the files to correct consistency errors in records and fields, trapped several hundred bad records into a "bad records" file and generated Arc/INFO coverages of all of the remaining data. Resulting point coverages were reprojected to UTM Zone 15 projection, NAD83 datum, horizontal units of meters. All of the original attributes were carried through into the GIS coverages, including altimeter readings, total intensity, diurnal value, FID number, flight line number, and other items unique to some of the files (e.g. vertical derivative for northeastern Mn flight areas). MnDNR-Lands and Minerals added UTM x-y coordinates to the coverages and converted them to Arcview GIS shape file format for more convenient downloading by GIS and non-GIS users through MnDNR's Data Deli internet site.
Source Scale Denominator	24000
Section 3	*Spatial Data Organization Information - - - - - - top*
Native Data Set Environment	Arc/Info Coverage
Geographic Reference for Tabular Data	None
Spatial Object Type	Point
Vendor Specific Object Types	Point
Tiling Scheme	State
Section 4	*Spatial Reference Information - - - - - - top*
Horizontal Coordinate Scheme	UTM
Ellipsoid	GRS1980
Horizontal Datum	NAD83
Horizontal Units	meters
Distance Resolution	meters
Altitude Datum	NGVD1929
Altitude Units	meters

Depth Datum	Not Applicable
Depth Units	Not Applicable
Cell Width	0
Cell Height	0
Latitude Resolution	0
Longitude Resolution	0
UTM Zone Number	0
SPCS Zone Identifier	0
County Coordinate Zone Identifier	0
Coordinate Offsets or Adjustments	None
Map Projection Name	
Map Projection Parameters	
Other Coordinate System's Definition	

Section 5	*Entity and Attribute Information - - - - - - top*
Entity and Attribute Overview	All of the original attributes were carried through into the GIS coverages, including altimeter readings, total intensity, diurnal value, FID number, flight line number, and other items unique to some of the files (e.g. vertical derivative for northeastern Mn flight areas).
Entity and Attribute Detailed Citation	

HTML Table

Section 6	*Distribution Information - - - - - - top*
Publisher	Minnesota DNR - MIS Bureau
Publication Date	6/12/2000
Contact Person Information	Robert Maki, GIS Database Coordinator Minnesota DNR 500 Lafayette Road, Box 11 St. Paul, MN 55155 Phone: (651) 297-2329 FAX: (651) 2974946 E-mail: robert.maki@dnr.state.mn.us
Distributor's Data Set Identifier	aeromagx

Distribution Liability	None stated
Transfer Format Name	6.0
Transfer Format Version Number	GeoTIFF
Transfer Size	43
Ordering Instructions	Contact above Person
Online Linkage	DNR Data Deli
Section 7	*Metadata Reference Information - - - - - - top*
Metadata Date	6/14/2000
Contact Person Information	Dave Dahl, GIS Specialist/Geologist DNR-Division of Lands and Minerals 1525 Third Avenue East Hibbing, MN 55155 Phone: (218) 262-7322 FAX: (218) 262-7328 E-mail: dave.dahl@dnr.state.mn.us
Metadata Standard Name	Minnesota Geographic Metadata Guidelines
Metadata Standard Version	1.2
Metadata Standard Online Linkage	http://www.lmic.state.mn.us/gc/stds/metadata.htm