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SPATIAL DATA ACCURACY AND ITS IMPORTANCE TO EFFECTIVE MINERAL EXPLORATION

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ABSTRACT

All data are spatially incorrect. This paper describes examples of where and how spatial accuracy of maps is important (or not) in effective exploration. Exploration projects may deal with many diverse data sets with a range of quantitative and qualitative accuracy. The spatial accuracy must be determined for each data set, in order to integrate the data set with others. Documentation must include qualitative as well as quantitative information about the data set.

Error is involved in initial field collection, tabulation, and in post-processing interpolation. This paper describes various data sets, their errors and how they can be documented and dealt with in a GIS for exploration environment. Map accuracy, generalisation, projection, and datum conversions are discussed.

INTRODUCTION

Effective exploration requires speed and accuracy to make a decision, whether it is to beat the competition on acquiring a property or to drill the discovery hole before management gets bored with the project. The availability and diversity of digital data that must be handled to make effective, competitive decisions requires a sound knowledge of the data accuracy. All data are wrong. How wrong depends upon the application, and within this framework we can move forward according to time and accuracy constraints.

This paper provides examples of exploration data integration, including airborne scanner data, ground geochemistry, and satellite imagery used on recent exploration programs in Nevada, U.S.A. and Chile. Examples are given of situations in which detailed rectification are and are not justified.

If the explorationist can return to previously sampled locations in the field then why waste any time on spatial accuracy? If a geochemical survey is the only basis of information, then an uncontrolled grid might be applicable. However, if the study includes other spatial data sets, such as multispectral satellite imagery, airborne or ground geophysics, then data integration can increase the effectiveness of the data exponentially. Data layers that are unrectified with respect to each other, such as different maps at different projections and scales, create endless problems in trying to resolve real patterns and thus limit their utility in exploration. It is important for project managers to understand when rectification is practical and when it is not.

Integrating data is important, but what may not be obvious is how accurately data can be rectified. The following two examples from exploration programs of Homestake Mining Company will describe examples of when detailed rectification is, and is not, important.

TWO EXAMPLES OF MAP RECTIFICATION

Nevada example

The first example is from Nevada where numerous gold mines exist and extensive exploration is undertaken by Homestake Mining Co. Here Homestake's integrated GIS/image processing architecture has consistently produced rapid results, because the data sets are rectified to within known errors.

In this example a geologist knew about a gold-bearing quartz-adularia system from previous work. A detailed satellite alteration map showed a distinct anomaly extending beyond the alteration known from field work. The immediate decision to stake the ground was based on the image with its alteration pattern and extent. As the project matured, detailed geochemical sampling demonstrated that the Thematic Mapper (TM) alteration pattern not only defined exterior boundaries for the gold, but also the gold values in soil mimicked the most intense part of the alteration pattern, as shown in Figure 1.

Figure 1 is a bubble plot of gold values from soils. The TM alteration map as an underlay demonstrates a close spatial coincidence between the yellow TM colors and the higher gold values.

The alteration map was produced using the "Crosta Technique" (Crosta and Moore, 1989) and the colouring as described by Loughlin (1990), in which red = iron oxides, green = iron oxides + clay, and blue = clay. In a Crosta image, alteration systems are typically yellow and involve a nonlinear combination of clay and iron oxide alteration. This technique has proven to be more discriminating relative to other methods in areas with some vegetation, as demonstrated by Bedell for the Comstock Lode area, Virginia City, Nevada (Sabine, in press). The coincidence of alteration and elevated gold in soil is unusual, as gold values

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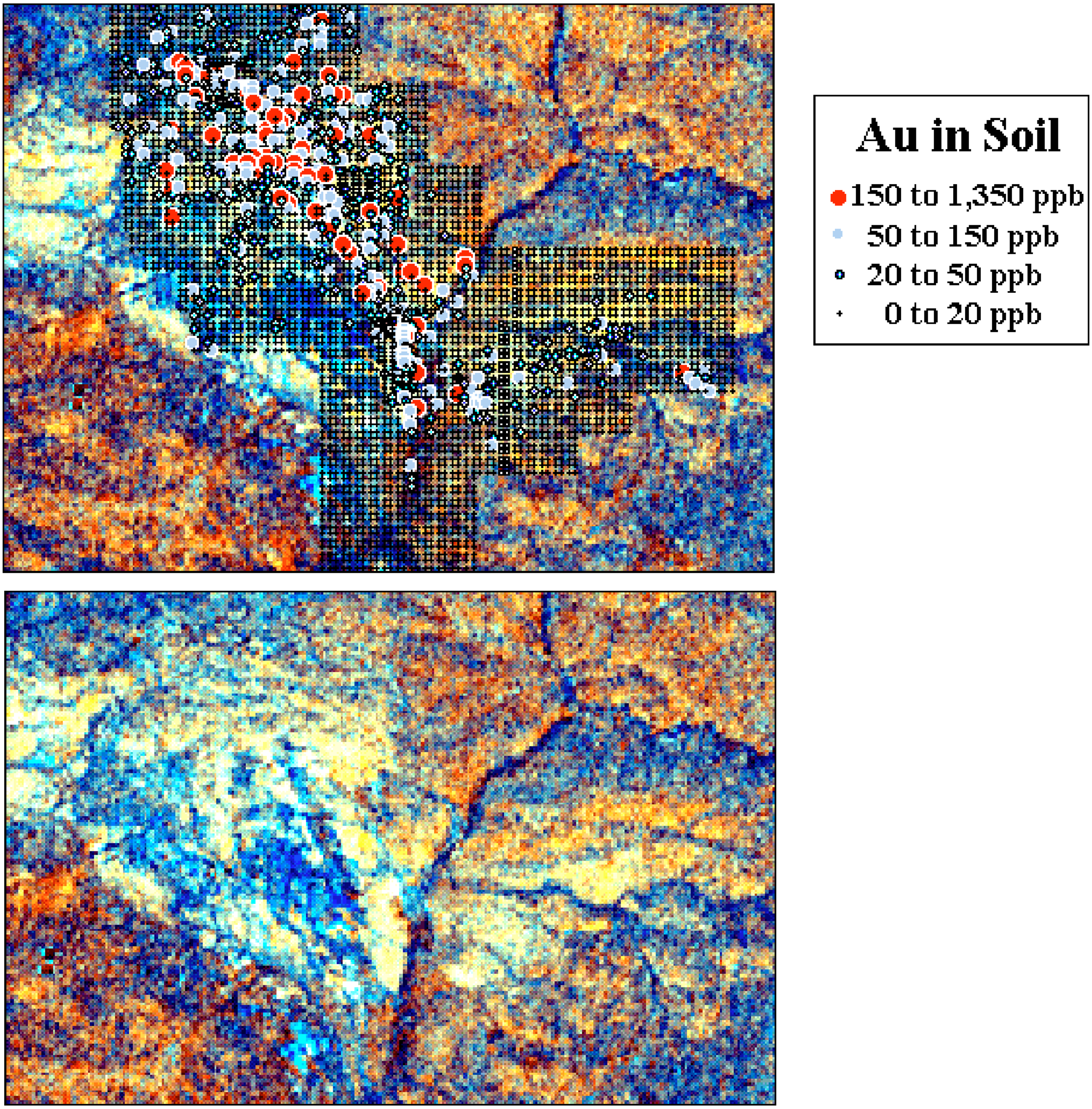


Figure 1: *Bottom: Landsat TM image (6.4 km across) showing most intense alteration in white. Red is iron oxide, blue is clay, and green is a mixture of both. Hence, white shows highly correlated iron and clay alteration. Top: soil sampling grid, showing correlation between gold values (large bubbles) and TM alteration anomaly.*

do not always follow alteration patterns. However, field geologists gained a significant confidence in this image for developing drill targets, and the spatial accuracy to which these data were integrated proved critical for this application.

This example demonstrates the use of rectified TM imagery from project inception through detailed fieldwork in defining drill targets. Correctly rectified imagery had a multiple benefit in directly obtaining accurate coordinates for staking, as well as for their later correlation with detailed ground geochemistry. The TM image was rectified to about one pixel or 30 m. The soil grid was mapped by chain and compass between posts established by a total station differential GPS to centimeter accuracy. Although the survey grade centimeter accuracy was not necessary, the efficiency of the GPS total station system was cost effective. The total station GPS allows a single surveyor to locate posts in real time by radio repeaters, thereby providing the differential correction. Hence, the spatial accuracy was better than needed, but the speed and cost at which the data could be obtained dictated the survey method.

Due to the number of the company's projects generated within the Great Basin, such detail can be justified. Homestake's other digital data sets for the region are also numerous and are usually accurate to within 50 m in plan.

Given accurately rectified data sets, rapid data access is provided at Homestake by dynamic linking of open UNIX software. The architecture includes Genamap GIS and ERMapper image processing software. A true dynamic link has been constructed and is now part of both systems. This link allows complete access to both systems simultaneously, in a single window, with no intermediate file production. Within ERMapper a layer can be added that initiates the link to Genamap. The ability of Genamap to be map-projection-independent greatly enhances processing speed. When a new layer of Genamap data is selected it simply reads the header file for whatever data are in the active window, and converts the data on the fly as it is displayed. All menus are configurable, which allows routines that are frequently used to be quickly implemented. The menu development is fully X Windows compliant and therefore can be used to drive any other open UNIX software. This not only allows the use of emulators (i.e. the ability to work on a UNIX box from a PC), but most importantly geologists only have to go into one system even though they may be using several software packages.

Rectification to single-pixel accuracy (30 m for TM) is required for matching soil geochemical data to TM-derived alteration patterns. This level of accuracy may seem extreme for exploration, but if one considers that dozens of mines and past projects may be present on any given TM scene, the extra cost is justified.

Chile example

The second example pertains to an area with fewer available data. The local maps that do exist are not spatially accurate. This area is near the El Hueso Mine, just east of the town of El Salvador in northern Chile.

A good test of spatial accuracy is to overlay the data layer to be tested with a rectified satellite image. Satellite data have nonlinear errors, but they are relatively minor, and the stability of the platform provides coverage with no significant random errors. If the accuracy of the test map differs significantly from one part to another, then the most reasonable explanation is that the test map has an unstable base. For example, the 1:50 000 maps available for the region have errors close to 1 km over distances of less than 10 km. This error is related to insufficient control on the base map. In this situation, it is best to choose an independent base and transfer the data to it (or do crude rectification), realizing that spatial uncertainty exists. Approximate rectification will allow coarse-scale patterns to be identified and followed up with detailed field work.

In this area, airborne scanner data were available from Geoscan. Consultants promised that they could rectify the data, but they would not define the accuracy. They promised that only the edges of the imagery were badly distorted due to the sweep at the extreme edges of each scan line. Although the errors involved in airborne scanning systems are large and random, scientists still attempt rectification (e.g., Fenstermaker and Miller, 1994). If you consider a scanner with a small Instantaneous Field Of View (IFOV) that scans from side-to-side on an aircraft close to the ground, in rugged terrain, it is apparent that any slight random movement of the aircraft would result in scale and perspective changes between IFOVs.

Homestake Mining Co. undertook a project to demonstrate the errors involved in these data. In a typical "rubber sheeting" exercise, control points are collected on the map or image to be warped *from,* and coincident control points are taken on the base map or image to be warped *to.* These control points are then used to calculate coefficients in a series of polynomial equations which define the nonlinear warping or "rubber sheeting". Control points were collected and computer algorithms were used to compute various polynomials to obtain errors associated with each control point. In this example, the errors were contoured from a first-order polynomial (Figure 2a). Notice in Figure 2a there is a particularly large error (232 m) at the upper right center, about one-third from the top of the figure. Comparing this error map with those obtained with second-, third-, and fourth-order polynomials, shows that this large value changes to 199 m on the second-order map (not shown here), to 167 m on the third-order map (Figure 2b), and 189 m on the fourth-order map (also not shown here). This level of accuracy is poor for 5-m pixels. The best polynomial to use in this instance is the third-order, but many errors well over 200 m still exist.

The errors in Figure 2 demonstrate that (1) errors are not concentrated in the middle of the data (as suggested by the consultants), and (2) higher-order polynomials do not necessarily converge on a stable solution. However, 200 m error is not acceptable for data with 5-m pixels.

In this situation, manually transferring features from an image to a stable base may be the most appropriate method. Interpreting anomalies from a distorted scanner image and vectorizing them on an adjacent computer window on a stable base such as a map or satellite image is recommended.

SPATIAL ACCURACY OF MAPS

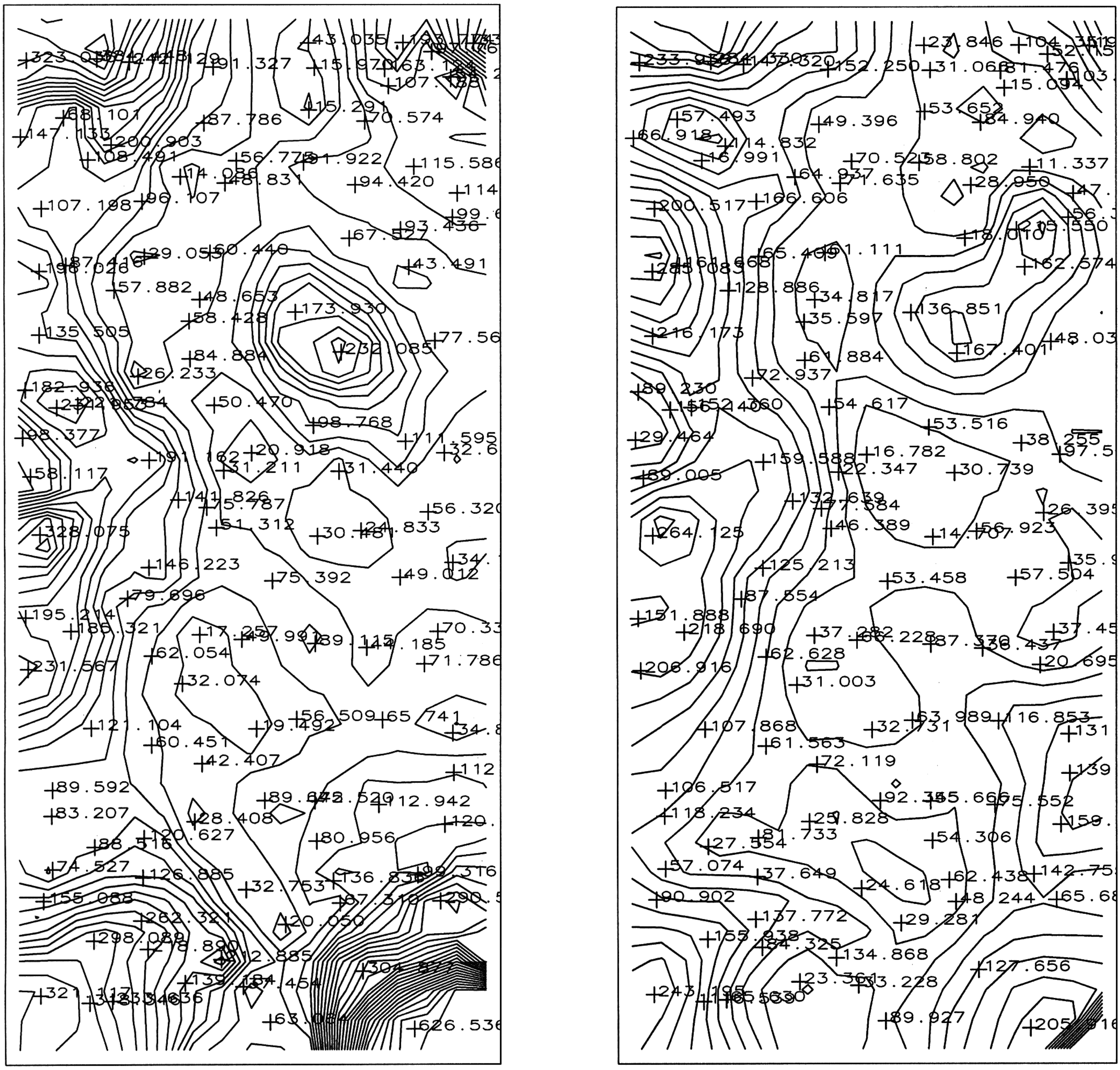
Maps for exploration come from a variety of sources, and the spatial accuracy of many of them cannot be trusted. However, maps published by government and by established private organizations have a certain level of accuracy which must be understood. Regardless of the source of the data, some or many of the following problems may exist: poor survey control, inappropriate generalisation, insuffficent documentation on projection parameters, and digitizing errors.

Survey control

A lack of survey control can create errors in various parts of a map sheet. This can often be detected with sufficient accuracy for exploration by rectifying the data to a stable satellite image, such as 30 m TM. If a frontier area has poor quality base maps, satellite imagery may be considered as a suitable base.

Generalisation

All maps are generalised and survey organizations have rules about generalisation that allow shifted features to be expanded for clarity. For instance, roads are often shown as lines thicker than the actual road. This widening of the road may force features like buildings to be displaced, and there are rules for these displacements. Fortunately for exploration,



By grid interpolation
1st order polynomial residuals
20' contours
scale: 1:50,000

By Kriging interpolation
3rd order polynomial residuals
20' contours
scale: 1:50,000

Figure 2: *Contours of residuals (RMS errors) obtained in rectifying Geoscan airborne scanner data to basemap using polynomial equations. (**a**) residual errors with first-order polynomial, and (**b**) third-order polynomial. Notice that errors are not restricted to edges of image.*

topographic features, rivers, and road center lines are usually not adjusted, whereas positions of cultural features are often compromised.

Projection changes

Homestake has many analogue maps which were made with various types of computer manipulation. One of the more frustrating problems in dealing with these maps has to do with the way new map projections are constructed.

A rather unusual example of analogue map transformation is demonstrated in Figure 3. This shaded relief map looks like a standard Digital Terrain Model (DTM) of the northeastern United States. It is actually a physical (analogue) model produced by the U.S. Army Map Service. The original 1 × 2 degree models were carved by hand. They were made using a Transverse Mercator projection. For such a large area the lines of

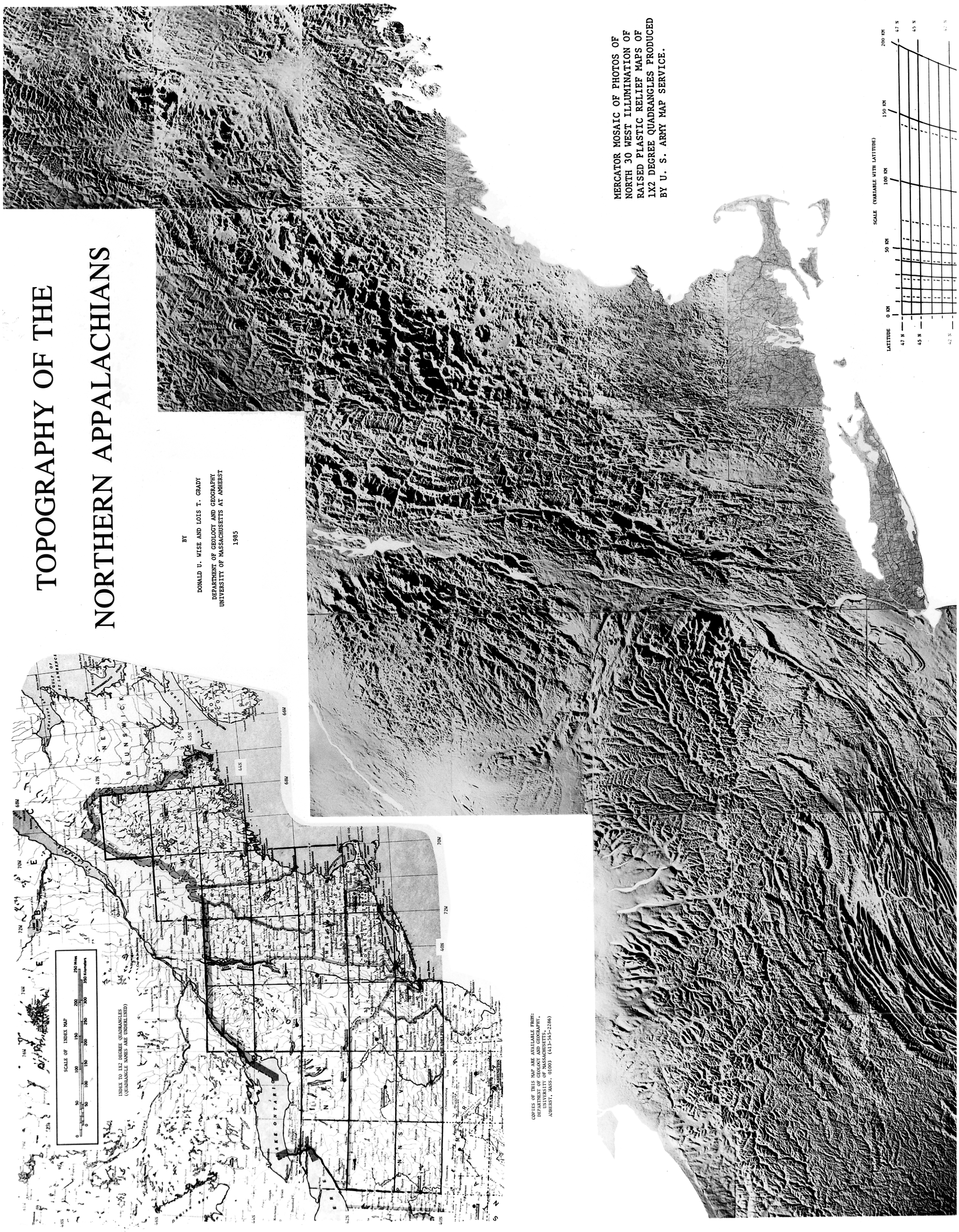


Figure 3: *Analogue terrain model produced by Dr. Don Wise at University of Massachusetts at Amherst. Model was hand carved and shaded with photo lamps to simulate shaded DTM. Individual models were rotated according to calculations to change projection from Transverse Mercator to Mercator projection. In this way north always remains parallel to vertical page axis throughout image, essential for quantitative lineament analysis.*

longitude converge appreciably towards the north pole, preventing a quantitative lineament analysis across the entire area (involving several adjacent models). Structural geologist Dr. Donald Wise (pers. comm.) wanted to combine several models for lineament analysis, and in order to maintain the orientation of the meridians from one model to the next, the projection had to be changed from a Transverse Mercator to a Mercator projection. Calculations were made to rotate each model a certain amount so that the overall shape of the combined models was in a Mercator projection. The models were then photographed with angled lights for a shaded DTM effect and published as a poster by the University of Massachusetts at Amherst. Note that now the overall shape of the model is in the Mercator projection, although the internal geometry of each 1 × 2 degree block is in the Transverse Mercator projection. Many maps throughout the world have been subjected to this kind of analogue treatment and it is important to be aware of the potential distortions.

Projection parameters

A frequent problem with integrating maps involves uncertainty about map projections and datums. Often the datum and projection information are not known even by chief surveyors in national organizations. However, if the map in question is to be integrated with other data sources, the projection information *must* be known; otherwise the absolute accuracy of spatial locations is uncertain, without independent control point data for rubber sheeting.

For example, Homestake made large 1:250 000 scale mosaics of the Great Basin with U.S. Geological Survey topographic maps, gravity and magnetics. Some of the 1:250 000 scale Transverse Mercator series USGS basemaps have their central meridians in the middle of the maps, others do not (Snyder, 1987, p. 57). This information is not published on the maps, and therefore critical information has been lost. This serves as an example of lost accuracy due to a lack of documentation.

Digital files may be transferred from organization to organization with no detailed projection information. Even if the projections are known, problems may occur with transforming the data. Certainly all projection changes should involve transformation to geographic coordinates (latitude/longitude) as an intermediate step to ensure stable spherical trigonometry (e.g., Steinwand *et al.*, 1995). It is also instructive to know the magnitude of the errors involved in projection conversion. For example, to determine the magnitude of the errors resulting from a conversion from geographic coordinates (assuming a spherical earth) to geographic coordinates using the WGS84 datum, the distance difference for points on a graticule were plotted and contoured, as shown in Figure 4. Errors up to 100 m occur in the western U.S., or even greater in the NW of Nevada, much of California, and all of Washington . and Oregon. Errors greater than 200 m occur for much of South America. Parts of southern Australia may actually have errors greater than 450 m.

In summary, the user needs to be aware of map projections, and datums. Exploration frequently will use data with no distinct topographic base-map control such as some geophysical data sets. Unknown errors such as datum shifts may not be discovered until too late. It is also important to understand the magnitude of digitizing errors, and how they compare to the accuracy standards of mapping agencies.

Digitizing accuracy

International standards of measuring accuracy of maps are important when working with data and changing map scale. Map accuracy is defined as the standard error of position (r_p). Acceptable accuracy is usually when 90% of all map features are within measuring accuracy on a map. The measuring accuracy (r_m) of most maps is usually taken to be between 0.3 and 0.5 mm. The standard error of position (r_m) is expressed with a map scale factor (s):

$$r_p = r_m \times s \qquad [1]$$

For example if the scale (s) is 1:1,000 000 this is equivalent to taking 1 mm on the map representing 1 km on the ground. If we multiply the 1 km by the measuring accuracy (r_m) at 0.3 then the standard error of position (r_p) will be 300 m.

Acceptable contour accuracy is when 90% of points on a contour are accurate in elevation to within half the contour interval. A useful compilation of standard errors is given in Table 1.

The values in Table 1 are guidelines for international standards and will vary from country to country. These numbers provide a guide for judging the potential error in integrating diverse data layers.

In constructing a digital data set it is desirable that the errors involved be *less* than the standard errors to which the map was made. For instance, a 1:100 000 scale map generally has an error in plan of 30 m with a measuring accuracy of 0.3 (Table 1). However, the measuring accuracy may vary and you may have to consult the organization which produced the map. The U.S. national map standard in Table 2 shows that the measuring error (r_m) is typically 0.508 instead of the 0.3 described in Table 1. When digitizing a map it is necessary to be at least as accurate as the measuring accuracy. According to Tables 1 and 2 digitizing should generally be between 0.3 and 0.5 mm.

In addition to digitizing accuracy, the paper map itself may be distorted due to shrinkage.

It is useful to keep in mind the above degrees of accuracy when merging spatial data acquired at different scales. For instance, examining

Table 1: ***Standard errors in plan and height (in meters) when measuring accuracy on a map is 0.3 mm (after Doyle, 1982).***

Scale	Plan	Elevation	Contour
1: 1 000 000	300	30	100
1: 500 000	150	15	50
1: 250 000	75	8	25
1: 100 000	30	6	20
1: 50 000	15	3	10

Table 2: ***Map scale and U.S. national map accuracy standards.***

Map scale (s)	Distance on map (r_m)	Distance on the ground (r_p)
1:100 000	.02″ (.508 mm)	166′ (50.6 m)
1: 50 000	.02″	83′ (25.3 m)
1: 24 000	.02″	40′ (12.2 m)
1: 15,840	.03″ (.76 mm)	40′ (12.2 m)

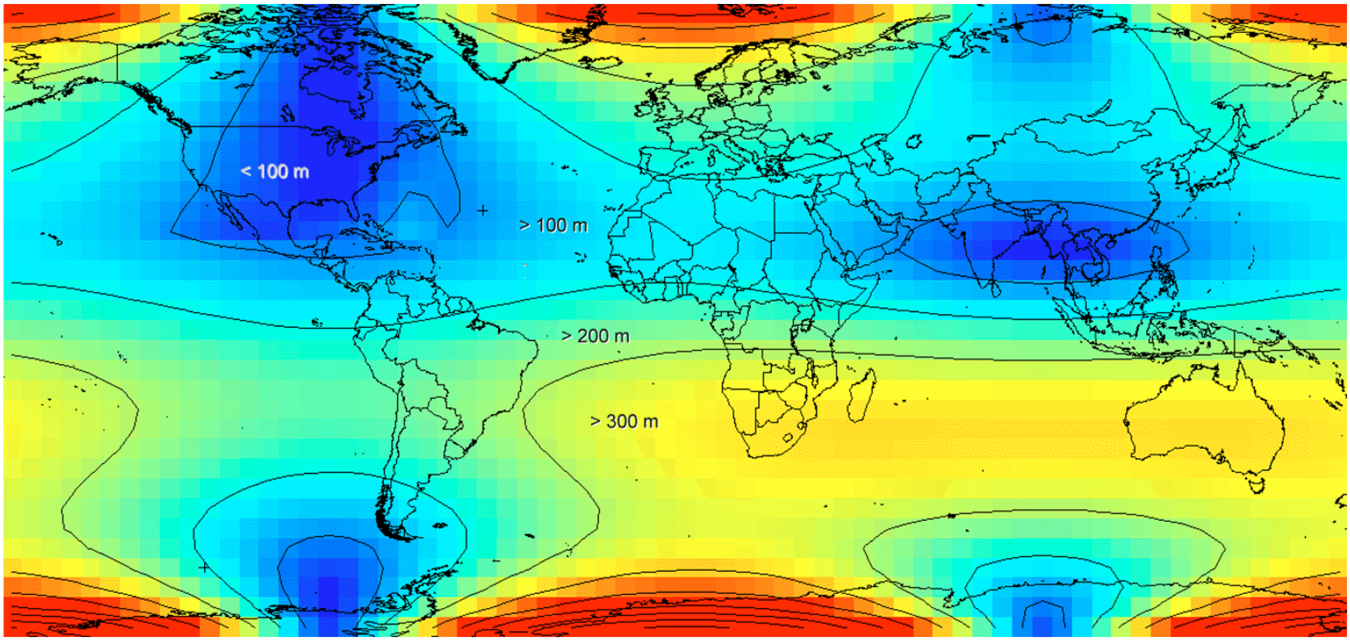


Figure 4: *Map of world showing combined grey scale and contour map of errors between latitude/longitude graticule for perfect sphere and for WGS84. Contours are at 100 m intervals. Dark areas are below 100 m, but lighter grey is over 300 m. Hence areas like North America have 50–150 m differences, and areas such as South America have 200 to nearly 300 m differences. Southern Australia may have errors greater than 350 m.*

1:500 000 scale contours overlain onto a full resolution TM satellite raster image with 30 m pixels, 90% of the points on the contours are at best within 150 m of their true position in plan. This will be even greater when considering hand-digitized contours where errors are typically around 0.5 mm which would make the error closer to 250 m.

RECTIFICATION

Because all data have errors, these errors are compounded when multiple data sets are visually or analytically compared. GIS is a tool of spatial data integration and therefore a tool of spatial *error* integration. In this context GIS can be thought of as error management. Rubber sheeting algorithms can be used to help minimize errors on individual data sets as well as the relationship between data sets. Often on a project one layer of data must be chosen as the base and other data sets rectified to it. The data set chosen as a base has errors associated with it, but it is the relative spatial error between the data sets that is important rather than their absolute position in the world. This need to minimize local distortions between data sets is why local grids are often used rather than universal grids.

Increasingly data are being collected with a GPS, using global coordinates, with greater accuracy, while decreasing surveying costs. This results in more direct survey data that can be stored directly in a universal grid such as UTM or in a latitude/longitude graticule. However, we will still have to bring in spatial data from maps and remote sensing imagery.

Remote sensing imagery is a valuable source of GIS data and has somewhat predictable distortion. Increasingly in the age of GPS, distortions may be minimized using parametric methods, i.e. the distortions are determined from known parameters. For remote sensing data a new era of system-corrected (parametric) rectification is beginning. Programming system parameters in conjunction with accurate locational information at the time of image acquisition will allow remote sensing data to be delivered geocoded.

However, most data still require non-parametric methods of rectification. The non-parametric method requires taking control points from an image or map you are warping *from* and another set of like control points from the data you are warping *to*. The algorithms employed are polynomial equations such as are used in curve fitting.

There are several pitfalls to be aware of in applying these algorithms:

1. The algorithms do not remove topographic distortion. Topography is random and a Digital Terrain Model (DTM) must be used to drape 2-D data over it to correct for elevation. The random topographic effects are minimized in flat terrain and data collected from high orbits.
2. The residual errors are only statistical. This does not guarantee levels of accuracy everywhere, however you can derive probabilities by contouring residuals and kriging.
3. Data outside of the control points have no guarantee as to their spatial accuracy. Typically, the higher the order the polynomial the worse the integrity of the data outside of the controlled area.
4. Collect more control points than are needed by the coefficients to the polynomial. Double the number of control points needed by the coefficients in the equation are mathematically preferred, but this can be difficult.

ERROR DOCUMENTATION

Documenting error is important both quantitatively and qualitatively. Absolute data such as control points and RMS are important to retain. The best place for this information is in a data set header. One may not even rectify the data, as it may not be important for the project, but at least the RMS indicates the accuracy of the data.

Other more qualitative information may be important. At Homestake we have employed a modification of the Spatial Data Transfer Standard (SDTS). This comprehensive document (FIPS 173-1A, 1992) tried to provide a basis for documenting accuracy for data in the U.S. government. There are five major headings to data quality: lineage, positional accuracy, attribute accuracy, logical consistency, and completeness.

At Homestake we use an additional file associated with our header file which contains the first three of these items. *Lineage* is important, because it states where the data came from. Information such as: "traced off a 1:50 000 scale airphoto enlarged to near 1:12 000 scale", or that the data are digitized by a certain person or company may be important. *Positional accuracy* should just include the control points, RMS, as well as any comments such as "poor spatial coincidence with swampy region in the NW of the image". This is useful because it may suggest a reason for lack of control in this area. *Attribute accuracy* is important for comments on geochemical and geophysical surveys, as well as expressing opinions on the ability of a certain lab to work with certain techniques, certain geologists to work on volcanoclastics, or quantify detection limits. *Logical consistency* refers to consistency of data structures and this may be topological (e.g., do all polygons close), or do all large deposits have a production table associated with them. This we view as document overkill, because one must always work with the data given, and this kind of information can be embedded in reports. *Completeness*, in our opinions is an unnecessary overhead, as it really refers to the objects on a map and not the quality of the objects representing a real-world feature.

Having lineage, positional accuracy, and attribute accuracy are important for storing quantitative and qualitative information relevant to exploration on-line. Other information accessed only occasionally can be gleaned from reports and does not require the cost of computer overheads to make it quickly accessible.

SUMMARY

In exploration, time is critical. One cannot afford either to overdo spatial accuracy, or to be unaware of the real errors involved. Awareness of the history of a data set and documentation of the provenance for later use is critical both qualitatively and quantitatively.

An example from Chile attempted to rectify data with non-systematic errors. A more satisfactory solution would have involved hand transferring the anomalies to a stable base map or satellite image. In the Nevada example, it was concluded that rectified data were of great assistance from the initial staking stage through the detailed geochemical program and establishment of drill targets.

A brief review of map accuracy and relevant aspects of map projections and datums demonstrates where errors might be introduced and to what magnitude. These errors can be minimized by a suite of readily available computer algorithms employing polynomials for rubber sheeting. The collection of control points and choice of the appropriate algorithm takes patience, skill, and an aptitude for knowing the data and the source of the errors.

An appropriate degree of documentation is important. Exploration is too dynamic and projects can be so diverse that being too stringent may defeat the purpose. If documentation is not easy and fast, chances are it will not be done at all.

In summary, spatial accuracy, like exploration geology, is in many respects in the realm of art rather than science. You just have to make sure that the famous quote from Maine U.S.A. does not apply to your project; "Come ta think of it, you can't get there from here" (Marshall Dodge, pers. comm., 1973).

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