PNL-10363
UC-606

Data Fusion Analysis of a Surface Direct-Current Resistivity and Well Pick Data Set

E. A. Clayton
R. E. Lewis

September 1995

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PNL-10363

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MASTER

Pacific Northwest Laboratory
Richland, Washington 99352

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SUMMARY

Pacific Northwest Laboratory (PNL) has been tasked with testing, debugging, and refining the Hanford Site data fusion workstation (DFW), with the assistance of Coleman Research Corporation (CRC), before delivering the DFW to the environmental restoration client at the Hanford Site. Data fusion is the mathematical combination (or fusion) of disparate data sets into a single interpretation. The data fusion software used in this study was developed by CRC.

This report discusses the results of evaluating a surface direct-current (dc) resistivity and well-pick data set using two methods: data fusion technology and commercially available software (i.e., RESIX Plus from Interpex Ltd., Golden, Colorado), the conventional method of analysis. The report compares the two technologies; describes the survey, procedures, and results; and includes conclusions and recommendations.

The surface dc resistivity and well-pick data set had been acquired by PNL from a study performed in May 1993 at Eielson Air Force Base near Fairbanks, Alaska. The resistivity survey data were acquired to map the top of permafrost in support of a hydrogeologic study. This data set provided an excellent opportunity to test and refine the dc resistivity capabilities of the DFW; previously, the data fusion software was untested on dc resistivity data. The DFW was used to evaluate the dc resistivity survey data and to produce a 3-dimensional earth model of the study area.

Although the conventional and data fusion methodologies are vastly different, the results were generally similar, with a few significant discrepancies. Brief overviews of each analysis method are listed below.

The conventional analysis requires significant user interaction at almost all stages of the evaluation. The user must have significant knowledge to operate the RESIX Plus software and be able to interpret the data to generate and choose the best models to pick the top of the permafrost. RESIX Plus final models are chosen based on fitting error, variance in equivalence analysis, and geological accuracy. The entire data reduction process using the conventional approach required approximately 50 person-hours.

Data fusion requires less interaction with the software; input is required only to define the earth model and its associated statistical parameters. Once the data fusion process is started, the user has no control over the evaluation process; nevertheless, the user should be knowledgeable regarding the nature and consistency of the data before using data fusion to best determine how the data should be edited and how much variance there is in equivalent solutions. Unlike RESIX Plus, model equivalence is not taken into account for the final model in the data fusion approach. The entire data reduction process using the data fusion approach required approximately 30 person-hours.

In many cases, data fusion may not be the best method to analyze dc resistivity data; however, data fusion may be useful for combining dc resistivity data with other data sets that are obtained using different electrical measurement methods.

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CONTENTS

SUMMARY iii

ACKNOWLEDGMENTS v

1.0 INTRODUCTION 1

1.1 Purpose and Scope 1

1.2 Background 1

2.0 TECHNOLOGY DESCRIPTION 3

2.1 Data Fusion 3

2.2 RESIX Plus™ Direct Current Resistivity Evaluation Software 3

3.0 TEST DESCRIPTIONS AND PROCEDURES 5

3.1 Data Acquisition 5

3.2 Data Reduction 5

3.2.1 Using RESIX Plus™ and Earth Vision™ 5
3.2.2 Using Data Fusion 5

4.0 RESULTS AND DISCUSSION 9

4.1 Using RESIX Plus™ and Earth Vision™ 9

4.2 Using Data Fusion 9

5.0 CONCLUSIONS AND RECOMMENDATIONS 39

6.0 REFERENCES 41

FIGURES

1 Map of Permafrost Study Area 6
2. Depth to Top of Permafrost Contour Map Generated Using RESIX Plus™ and Earth Vision™ 13
3. Example of RESIX Plus™ Results For a Resistivity Sounding 17
4. Resistivity Earth Model Generated Using Data Fusion (12 Meter Grid) 21
5. Depth to Top of Permafrost Contour Map Generated Using Data Fusion (12 Meter Grid) 25
6. Normalized Well Residuals From Data Fusion 29
7. Resistivity Earth Model Generated Using Data Fusion (40 Meter Grid) 33
8. Depth to Top of Permafrost Contour Map Generated Using Data Fusion (40 Meter Grid) 37

1.0 INTRODUCTION

1.1 Purpose and Scope

Data from a direct-current (dc) resistivity survey was evaluated using the Hanford Site data fusion workstation (DFW) to produce a 3-dimensional resistivity earth model of the study area.

Pacific Northwest Laboratory (PNL) has been tasked with testing, debugging, and refining the DFW, with the assistance of its developer, Coleman Research Corporation (CRC), before delivering it to the environmental restoration client at the Hanford Site.

A surface dc resistivity and well-pick data set had been acquired by PNL from a study performed in May 1993 at Eielson Air Force Base near Fairbanks, Alaska. The resistivity data had been evaluated by PNL using commercially-available dc resistivity evaluation software; this evaluation task required a significant amount of user interaction and interpretation (Gilmore et al. 1994).

The resistivity survey data were acquired to map the top of permafrost in support of a hydrogeologic study. The purpose of using the DFW to interpret the data set was to evaluate the use of data fusion technology on dc resistivity data, a previously untested utility of the DFW.

The data had been evaluated using a conventional method, the dc resistivity analysis software package RESIX Plus™ from Interpex Ltd., Golden, Colorado. From the RESIX Plus™ analysis, an interpretation of the depth from the ground surface to the top of the permafrost for each resistivity sounding had been made. The analysis results were combined with available well-pick data and gridded to create a top-of-permafrost surface map using Earth Vision™ software.

This data set provided an excellent opportunity to test and refine the dc resistivity capabilities of the DFW, a utility that was previously untested. The results and the methodology of the data fusion technology were compared directly with those from the conventional approach to evaluate the strengths and weaknesses of the data fusion method for handling dc resistivity data.

This report includes the conventional and data fusion technologies (Section 2.0), test descriptions and procedures (Section 3.0), results and discussion (Section 4.0), and conclusions and recommendations (Section 5.0).

1.2 Background

Data fusion is the mathematical combination (or fusion) of disparate data sets into a single interpretation. The data fusion software used in this study was developed by CRC for the U.S. Department of Defense (DOD). CRC adapted this technology for the environmental mission of the U.S. Department of Energy (DOE). CRC's initial adaptation efforts have been focused at the Hanford and Savannah River sites (Porter et al. 1994).

CRC's platform for its data fusion software is the DFW, a Silicon Graphics Onyx, UNIX-based workstation. In addition to the data fusion software, the DFW contains Dynamic Graphics Earth Vision™ visualization software; INGRES relational database; a user interface developed with INGRES 4GL; and some groundwater and geostatistical software.

2.0 TECHNOLOGY DESCRIPTION

2.1 Data Fusion

Data fusion combines data from multiple sensors. The results of data fusion allow users to make inferences about data that may not be possible from a single sensor alone. Data fusion is a mature technology that was developed for military applications, robotics, traffic control, and office management (Hall 1992).

CRC's implementation of data fusion uses a nonlinear, least-squares model to mathematically fuse various sensor data into a single interpretation. The mathematics were developed to calculate the position of orbiting bodies (Bierman 1977). The technology has been refined significantly, and the system developed for the Hanford Site fuses surface geophysical data (e.g., seismic refraction, seismic reflection, dc resistivity, frequency domain electromagnetics, and/or time domain electromagnetics) with stratigraphic contacts interpreted from well data.

The CRC system applies commercially available forward models to a pre-defined earth model of a site. The dc resistivity forward-modeling code used in the DFW is taken from the RESIX Plus™ software. The earth model is a series of 3-dimensional polynomials, with horizontal spatial coordinates as the independent variables, and either subsurface layer depth or values of various properties within these layers (e.g., compression wave velocity, resistivity) as the dependent variables. The results of the forward models are compared to actual site data and residuals are computed. An iterative, least-squares regression process ensues where the earth model is adjusted step-wise until the forward models and measurement data agree within set statistical parameters. Sophisticated optimization algorithms are used to adjust the earth model during this iterative process.

For each earth model polynomial, a number of parameters define and influence the data fusion treatment:

- order of the polynomial
- initial mean values of the coefficients for each term
- standard deviation (sigma) for each coefficient
- overall sigma
- exponential correlation coefficient
- minimum and maximum allowable values of the polynomial.

In addition to polynomial order and coefficients, coefficients have sigmas because they are random variables. The overall sigma is the standard deviation of the random variation about the polynomial mean, and the exponential correlation (tau) is defined as the distance at which the correlation between spatial points decays to 1/e (0.37) (Gibbs 1993). The minimum and maximum allowable values are the overall limits on the polynomial. The grid size and spacing for the problem are also defined in the earth model. Each data measurement entering data fusion has a user-assigned sigma as well. The influence of each of these parameters on the data fusion results is discussed in a qualitative analysis of data fusion sensitivity (Clayton and Lewis 1995).

2.2 RESIX Plus™ Direct-Current Resistivity Evaluation Software

RESIX Plus™ is a forward- and inverse-modeling, DOS-based software package for interpreting dc resistivity sounding data to depict a layered-earth (1-dimensional) model.

Following data reduction for each measured sounding curve, the user prescribes a best-guess geoelectric section model (depth versus resistivity). The software generates a synthetic resistivity sounding curve (resistivity versus electrode "a" spacing) from a geoelectric section model using linear filters. The user refines the model, if necessary, to obtain a better fit between the synthetic and actual sounding curves by adjusting model parameters: resistivity, thickness, and/or number of layers.

Once the synthetic and actual sounding curves are refined by the user, the geoelectric model is entered into the inversion routine, which uses ridge regression to iteratively adjust the model by varying layer thickness and resistivity to obtain the best fit between the synthetic and actual sounding curves. The user can also mask aberrant data points on the measured sounding curve, which makes those points transparent to software calculations. If the fit between the sounding curves is unsatisfactory after the inversion routine, the user can repeat the whole process using a different starting model with, for example, a different number of layers. Arriving at a best-fit geoelectric model is very much an iterative process and requires a significant amount of user input and interpretation.

Once a satisfactory best-fit geoelectric model is generated, the user can have the software perform an equivalence analysis to show alternative models that fit the data nearly as well as the best-fit model, but differ from it in terms of depths and/or resistivities. The software generates alternative models by setting an error threshold that is 1.2 times the best-fit error, and then varying the model to find the alternative that produces a fit equal to this error threshold. This process is done twice for each model parameter (layer thickness and resistivity), once to find the upper bound, and once to find the lower bound, which provides insight into how well bounded the model is.

3.0 SURVEY DESCRIPTIONS AND PROCEDURES

3.1 Data Acquisition

A dc resistivity data set was recorded at a Eielson Air Force Base near Fairbanks, Alaska, in a flat flood plain to map the depth to the top of the permafrost. The permafrost surface can be identified by locating the boundary between the lower resistivity, unfrozen topsoil and the higher resistivity, frozen soil (permafrost) beneath it. The surface dc resistivity method measures resistivity to different depths by varying the electrode spacing. The electrode array used in this study was a Wenner array, where four electrodes are arranged along a line, with equal spacing between all electrodes. For each survey line, apparent resistivity readings were made for a range of electrode ("a") spacings to produce an apparent-resistivity-versus-"a" - spacing sounding curve. Fifteen dc resistivity soundings were measured, resulting in 15 apparent-resistivity-versus-"a"-spacing sounding curves (see Figure 1 for a map of the study area and sounding lines). The sounding curves were used as input to RESIX Plus™ and the data fusion software. In addition to the resistivity data, five groundwater monitoring wells on the site with geologic logs indicated the depth at which the soil became frozen. The depths indicated by the monitoring wells were used as a second data set, the "well-pick data" in data fusion.

3.2 Data Reduction

3.2.1 Using RESIX Plus™ and Earth Vision™

Each sounding curve was smoothed by masking aberrant data points (e.g., points scattered from the curve profile because of excessive noise). A first-guess geoelectric section model was constructed and entered into the RESIX Plus™ software's forward modeling routine to produce a synthetic sounding curve. The model was refined manually to get a close fit between the synthetic and measured sounding curves, and it was entered into the inversion routine. Once a good-fitting model was obtained, an equivalence analysis was performed to determine how well bounded the model was. Models with different numbers of layers were also tried and compared with each other. The final geoelectric model chosen for each sounding curve was determined on the basis of best-fit, minimal variance in equivalence models, and geologic accuracy. The top of the permafrost was selected from the final models by locating the top depth of the first substantial layer from the ground surface with a resistivity greater than 1,000 ohm-meters.

The top of permafrost picks from the resistivity soundings were combined with the well picks and gridded in Earth Vision™ to create a top-of-permafrost surface map. The default grid spacing of 12 meters, calculated by Earth Vision™ to be the largest spacing that will still honor all the data points, was used. The entire data reduction process using this approach required approximately 50 person-hours.

3.2.2 Using Data Fusion

The data fusion software user interface is an INGRES 4GL, which allows the user contact only at the beginning and end of each data fusion run. Because of the interface, the user must edit the data, set up measurement files, create an earth model file, and set up the run control file without any feedback from the software. Setting up the measurement files entails arranging the edited resistivity data and well-pick data in two separate files in the correct formats. Each data point must be given a standard deviation (sigma) as well. The resistivity data points were assigned a sigma, which was approximately 5% of the measured value, and

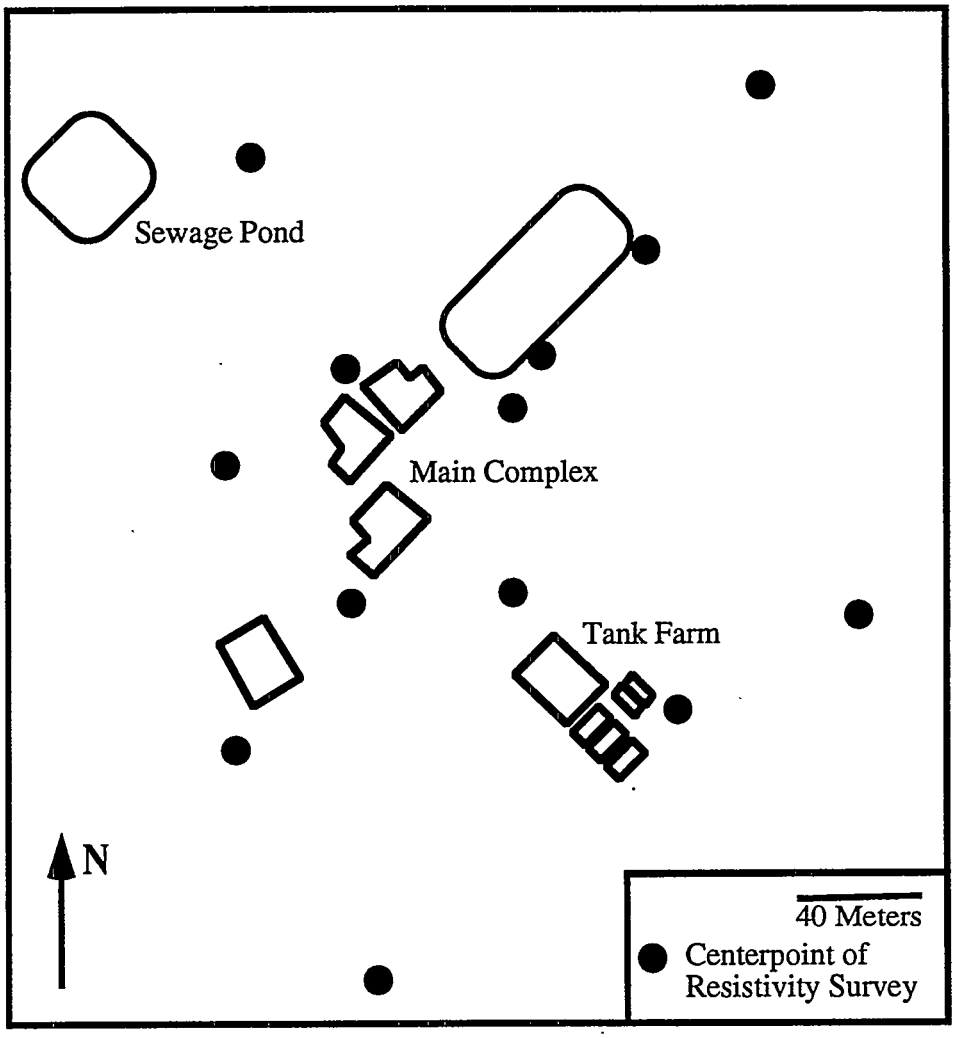


Figure 1. Map of Permafrost Study Area

the well picks were given sigmas that varied between 0.3 and 1 meter. The well-pick sigmas were based on the potential depth error in the determination of top permafrost by a geologist.

The data fusion software requires the same number of layers to be used for all resistivity soundings (in this case, a simple two-layer model was used). Thus, the resistivity data for data fusion had to be more thoroughly edited than it was for the RESIX Plus™ evaluation. The earth model, in this problem, represented the initial geoelectric section that data fusion worked on, but it also defined the grid spacing and a number of input parameters that determined how the problem would be treated by data fusion. Two different grid spacings were tried: 40 meters and 12 meters. The 12-meter spacing was chosen to match the grid spacing used in RESIX Plus™ and Earth Vision™ approach to the problem. Second-order polynomials, using the software defaults for coefficient sigma values, were employed to represent the depth from the ground surface to the top of the permafrost layer and the resistivities of the top and bottom layers in the two-layer earth model, for a total of three polynomials. These polynomials were set to constants of 3.5 meters, 100 ohm-meters, and

2,000 ohm-meters for the depth to the top of the permafrost layer, the top-layer resistivity, and the bottom-layer resistivity, respectively, to represent a layer-cake, horizontally homogeneous earth. The top and bottom layer resistivity polynomials were assigned overall sigmas of 50 and 500 ohm-meters, respectively, and taus of 120 meters. Several combinations of values for the width polynomial sigma and tau were tried before a successful data fusion run was completed. The final sigma and tau values used for the width polynomial were 2.5 meters and 120 meters, respectively, for the 40-meter grid spacing run. The width polynomial sigma was increased to 3 meters for the final 12-meter grid spacing run. A run control file was created to incorporate the proper measurement and earth model files and to allow for enough data fusion iterations to permit convergence.

Once the input files were created, data fusion was left to converge on a solution. Numerous data fusion runs were performed with different earth model parameters and/or more carefully edited resistivity data to produce an acceptable result. The entire data reduction process using data fusion required approximately 30 person-hours.

4.0 RESULTS AND DISCUSSION

4.1 Using RESIX Plus™ and Earth Vision™

From the 15 resistivity soundings recorded, 13 were used with 6 well picks to construct the top of permafrost surface contour map (Figure 2). Two of the soundings were rejected because of abnormal sounding curves that could not be modeled accurately or realistically. Each sounding was analyzed separately using RESIX Plus™, resulting in a best-fit geoelectric model and the associated equivalence models (Figure 3). The software also provides a fitting error for the model that is essentially the percentage difference between the model's synthetic sounding curve (generated from forward modeling) and the measured sounding curve. Most of the final best-fitting geoelectric models contained more than two layers and the user had to interpret which layer represented the permafrost.

The final contour map showing the depth from the ground surface to top of permafrost, generated in Earth Vision™, exhibits a diagonal ridge at the center of the grid, bordered on each side by troughs (Figure 2). The ridge has a high of 1.6 meters below ground surface (mbgs), which slopes to a low of 9.2 mbgs to the southwest and 6.7 mbgs to the northeast. At the southwest corner of the grid, a steep gradient in the top of permafrost surface was caused by a large discrepancy between a well pick (9.2 mbgs) and an adjacent interpreted resistivity sounding (4.0 mbgs). The five other well picks (at the center of the grid) agree quite well with the surrounding interpreted resistivity soundings. Note that Earth Vision™ forced all interpreted resistivity soundings and well picks to be honored in the gridded contour map.

4.2 Using Data Fusion

A first data fusion run was attempted using the unedited dc resistivity data, and did not converge on a solution. Several more runs were attempted, each with increased editing of the measured resistivity soundings. The data fusion finally converged when the two abnormal soundings that caused problems with the RESIX Plus™ analysis were not included and the data for "a" spacings of less than 1.25 meters were deleted. Removing the short "a" spacings eliminated data that might be affected by thin, shallow beds that were not representative of the depth to continuous permafrost. Thus, they represented noise in this problem if not taken into account by the interpreter (or interpreting software). The 40-meter grid spacing problem (8- by 9-grid size) converged in 8 iterations and took less than 3 minutes to complete on the DFW. The 12-meter grid spacing problem (18-by-27 grid size) converged in 8 iterations as well, but required approximately 8 hours to complete on the DFW.

The data fusion results for the 12-meter grid spacing run are shown in Figures 4 and 5. Figure 4 is a 3-dimensional depiction of the geoelectric section for the problem grid; Figure 5 is a contour map of the depth from the ground surface to the top of permafrost surface. Both figures were created in Earth Vision™ using data fusion output grid files. Figure 4 shows the top (ground surface) layer having a resistivity in the range between 0 and 500 ohm-meters and the bottom (permafrost) layer having a resistivity in the range between 1500 and 2500 ohm-meters. The actual resistivities of the subsurface fall beyond the objective of the study (i.e., to map the top of the permafrost). The permafrost surface from these results has a high of less than 1 mbgs located north-northeast of the grid center, and a low of 10.5 mbgs, located west-southwest of the grid center (Figure 5). Three other peaks in the surface result in a fairly complex structure. There is a steep gradient between the high in the center of the grid (~ 2 mbgs) and the major trough (10.5 mbgs).

The data fusion 12-meter grid spacing results are similar to the RESIX Plus™ results. Both sets of results have a ridge in the permafrost surface running generally north-northwest

to south-southeast across the grid, and both have a peak near the center of the grid. However, the two sets of results differ in that the data-fusion-derived permafrost surface has a major peak of ~ 1 mbgs and the RESIX Plus™-derived surface has a low of ~ 6.7 mbgs. The difference is caused by a difference in the solution of a resistivity sounding at that point. In the data fusion results, the structure of the top-of-permafrost surface has significantly more complexity and a deeper trough in the southwest corner of the grid than is shown in the RESIX Plus™ results.

A grid created in Earth Vision™ of the normalized well residuals (well residual divided by the sigma assigned to that well pick) from the data fusion results is shown in Figure 6. The well residual is the difference between the well pick and the depth to the top of permafrost calculated by data fusion at the position of that well pick. A normalized well residual greater than one or less than negative one indicates the well residual is greater than the assigned sigma. There are two well residuals that fall into that category. The excessively high normalized well residual of 4.6 in the southwest corner is probably caused by a discrepancy between the well pick and the adjacent resistivity sounding, a problem that was observed in the RESIX Plus™ results.

The data fusion results made with a grid spacing of 40 meters are similar to those from the 12-meter-grid-spacing run, except that the peaks and troughs in the top of permafrost surface are slightly sharper and more defined in the 40-meter grid spacing, and there is a much deeper depression just northwest of the center of the grid (Figures 7 and 8). The difference in the depression appears to be caused by a difference in the software interpretation of a resistivity sounding at that point.

FIGURE 2. Depth to Top of Permafrost Contour Map Generated Using RESIX Plus™ and Earth Vision™

Top of Permafrost From EV (MBS)

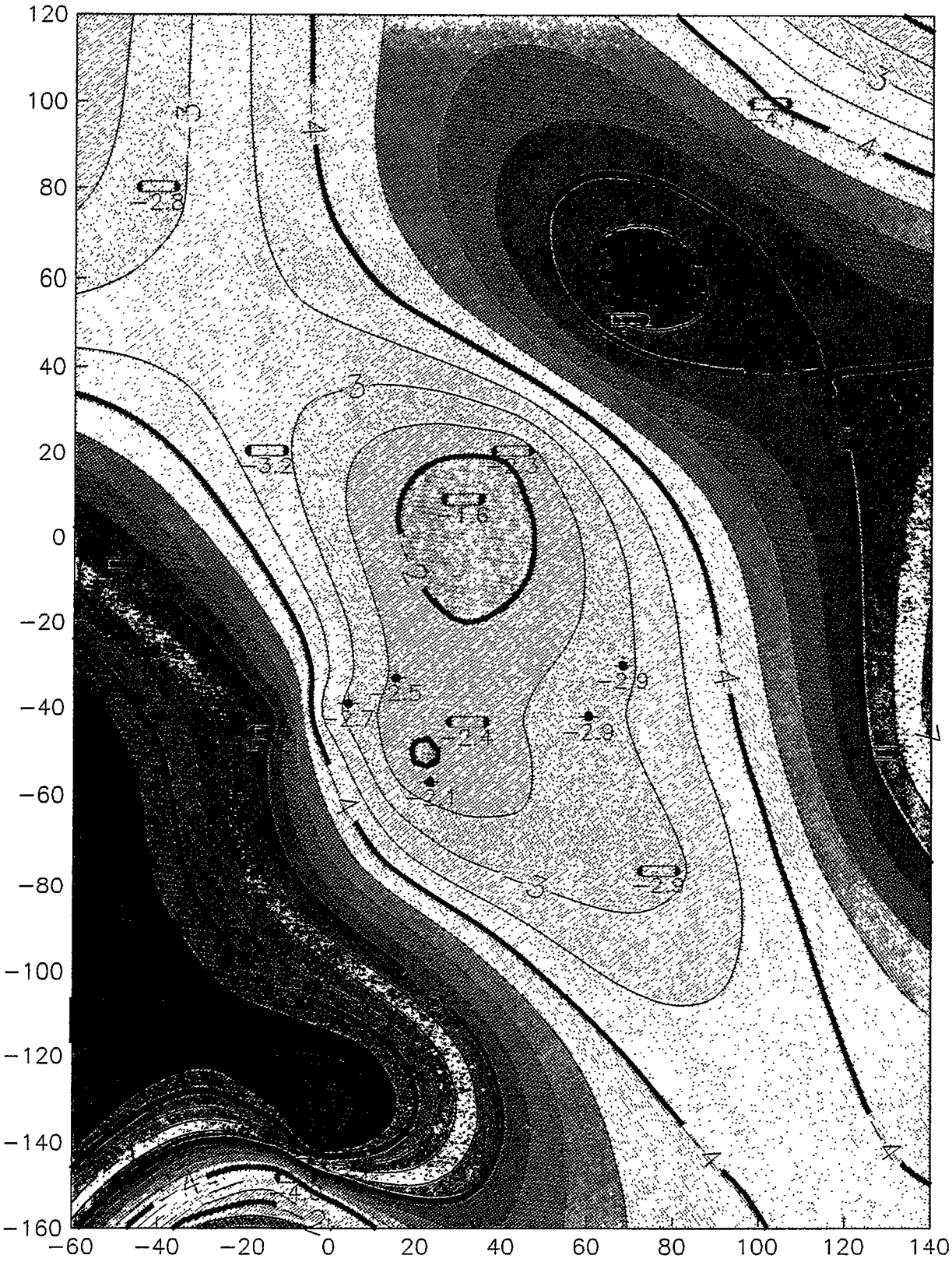
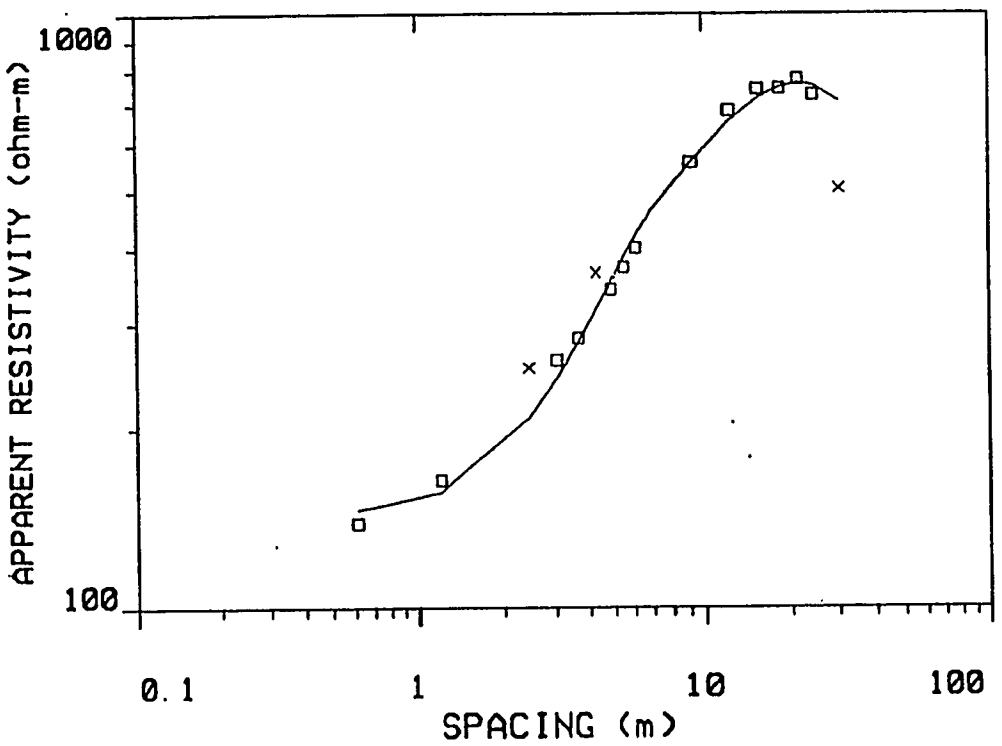


FIGURE 3. Example of RESIX Plus™ Results For a Resistivity Sounding


1000
100
APPARENT RESISTIVITY (ohm-m)
0.1
1
10
100
SPACING (m)

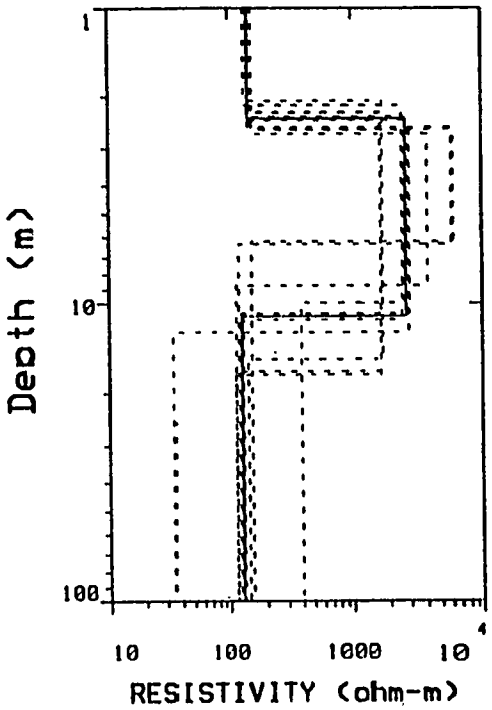

1
10
100
Depth (m)
10
100
1000
10
RESISTIVITY (ohm-m)

FIGURE 4. Resistivity Earth Model Generated Using Data Fusion

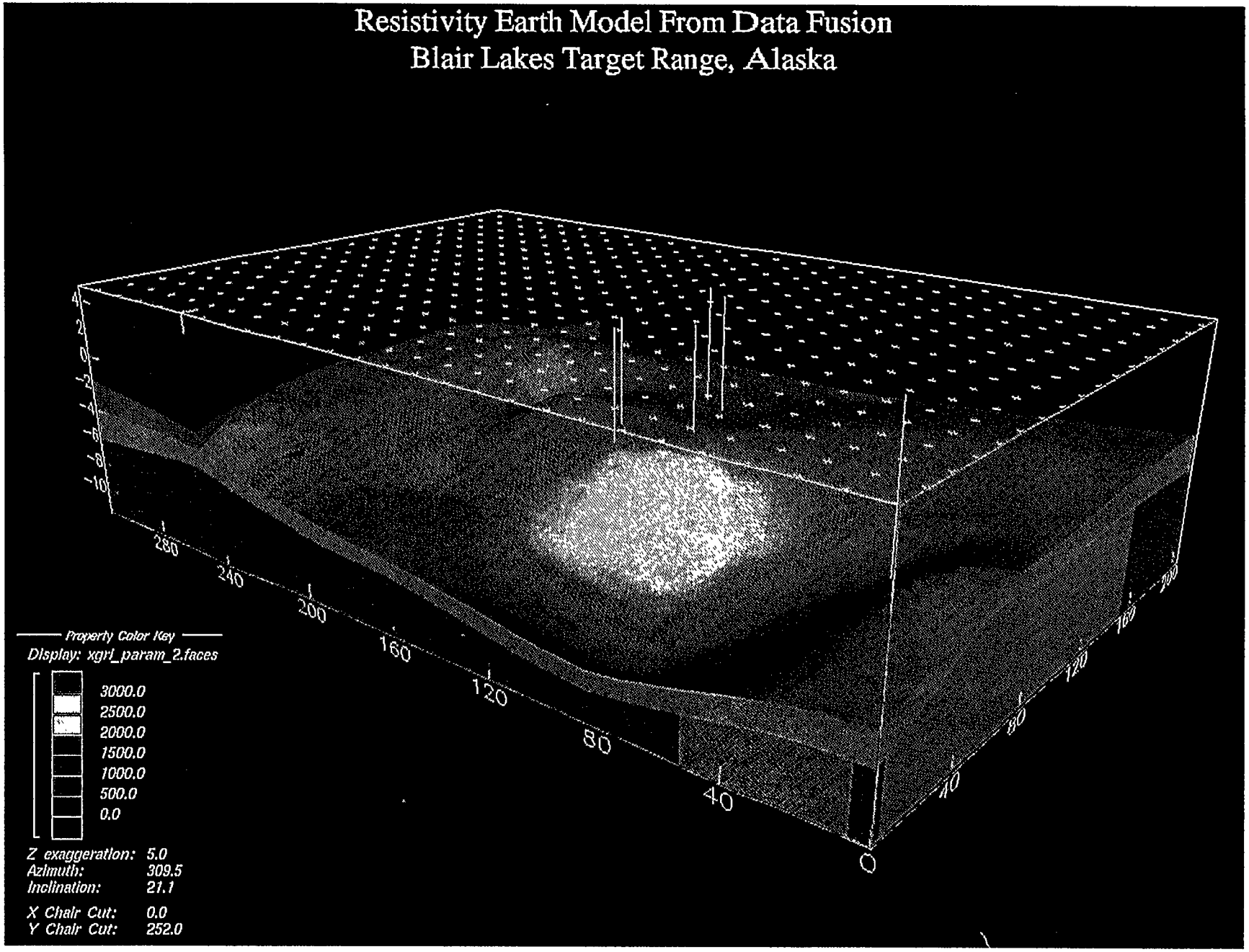
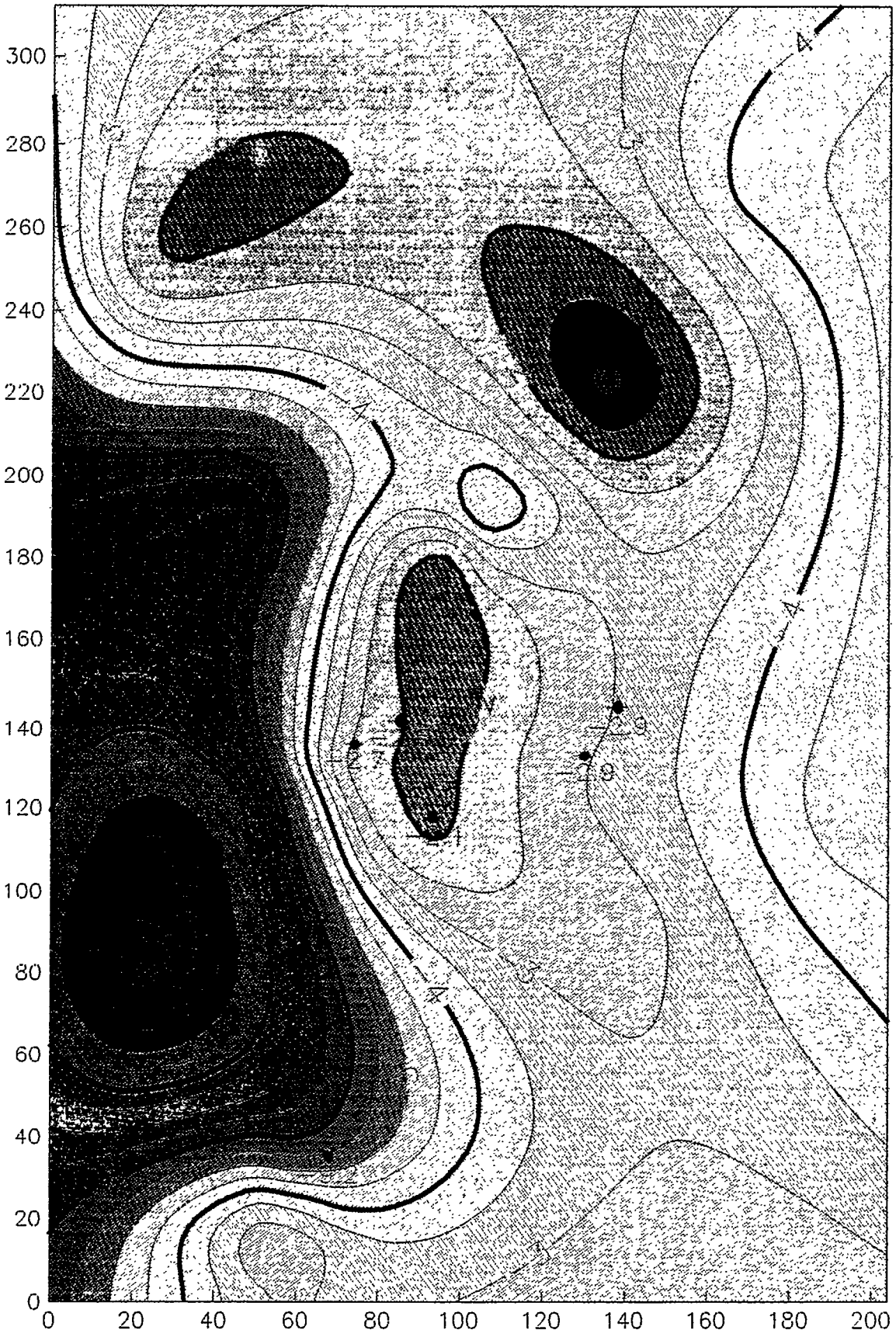

Resistivity Earth Model From Data Fusion
Blair Lakes Target Range, Alaska
Property Color Key
Display: xgrl_param_2.faces
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Z exaggeration: 5.0
Azimuth: 309.5
Inclination: 21.1
X Clair Cut: 0.0
Y Clair Cut: 252.0
280
240
200
160
120
80
40
0
40
80
120
160
200

FIGURE 5. Depth to Top of Permafrost Contour Map Generated Using Data Fusion

Top of Permafrost From Data Fusion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160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180
200
4
4
4
4
5
5
5

FIGURE 6. Normalized Well Residuals From Data Fusion

Normalized Well Residuals From Fusion

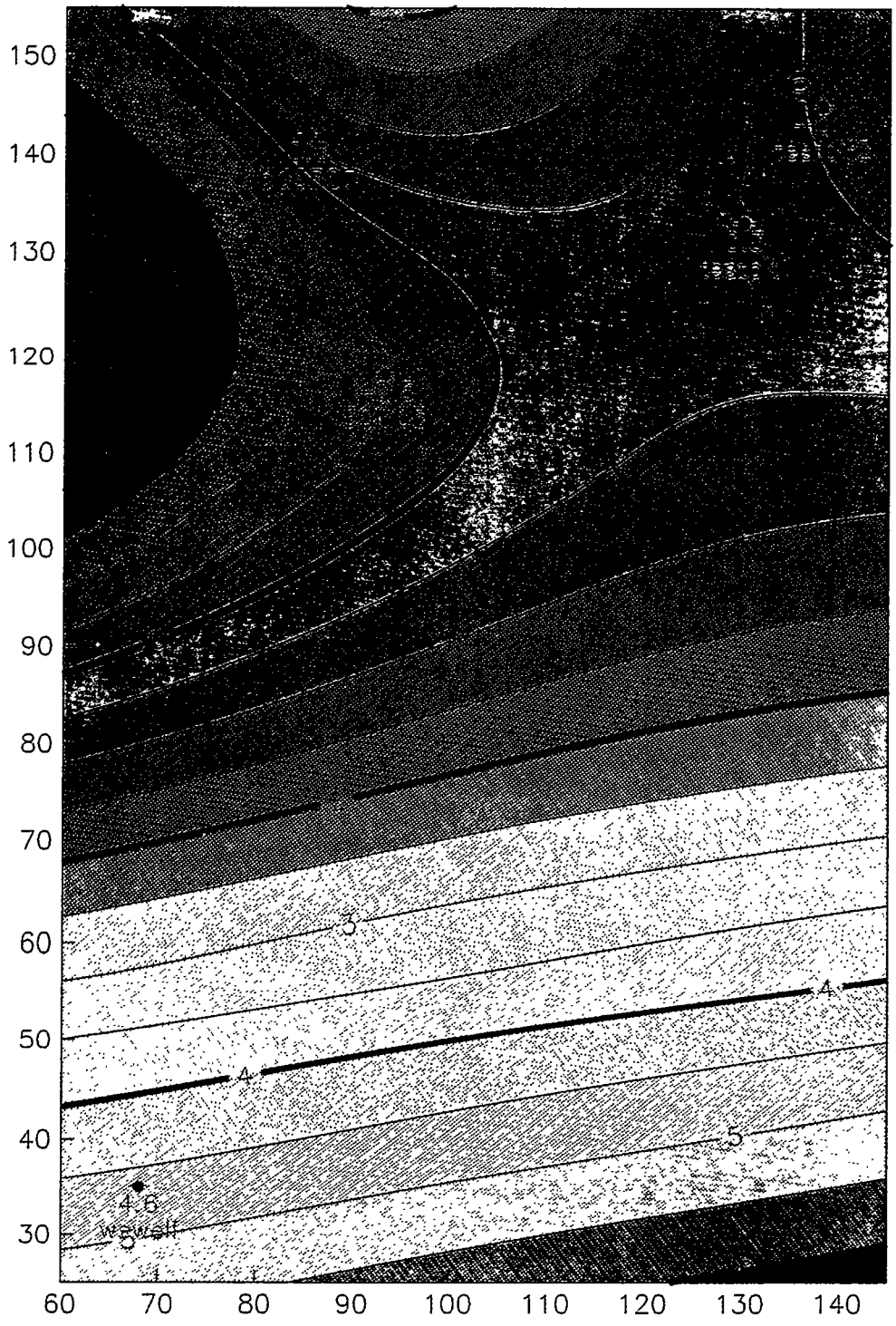


FIGURE 7. Resistivity Earth Model Generated Using Data Fusion

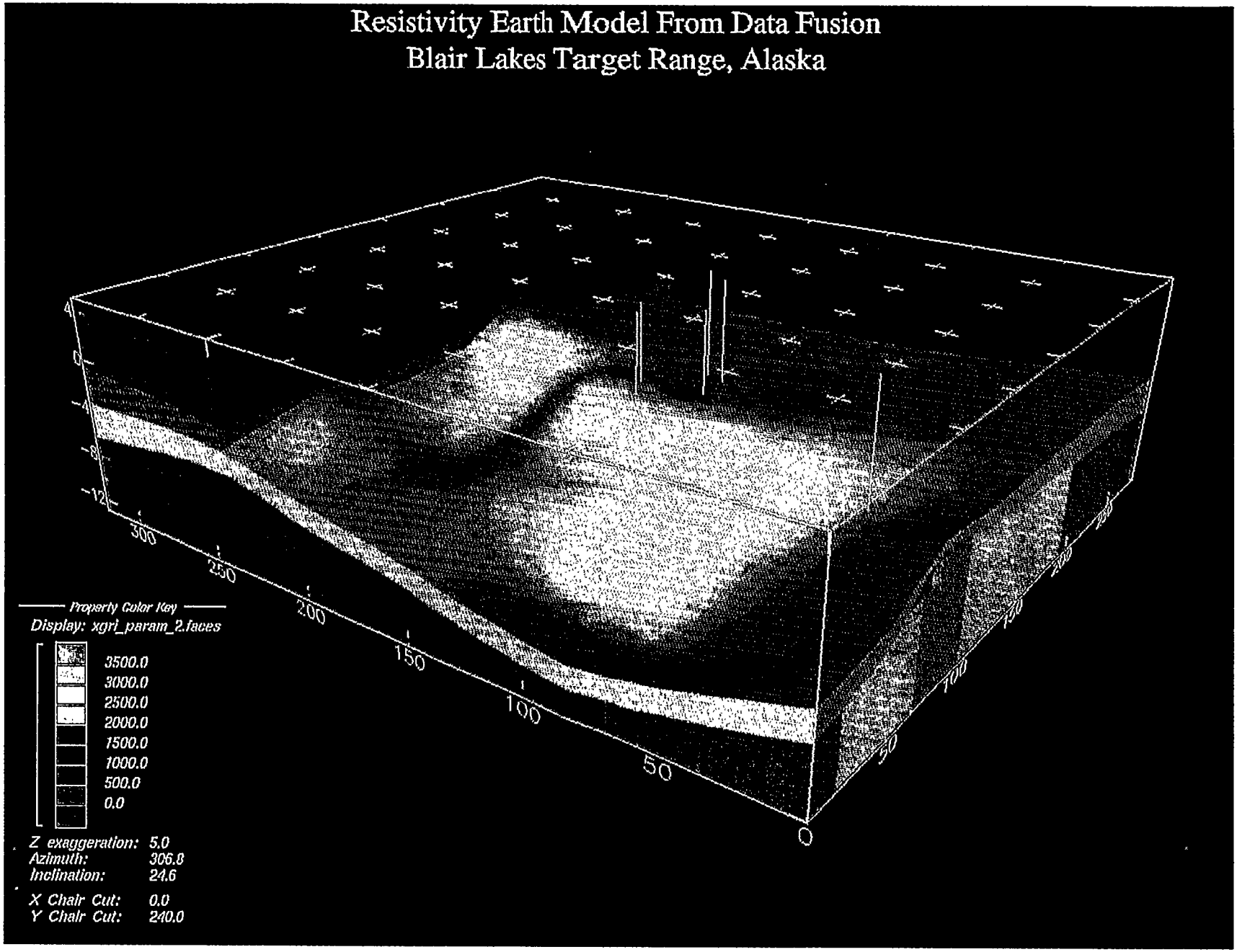
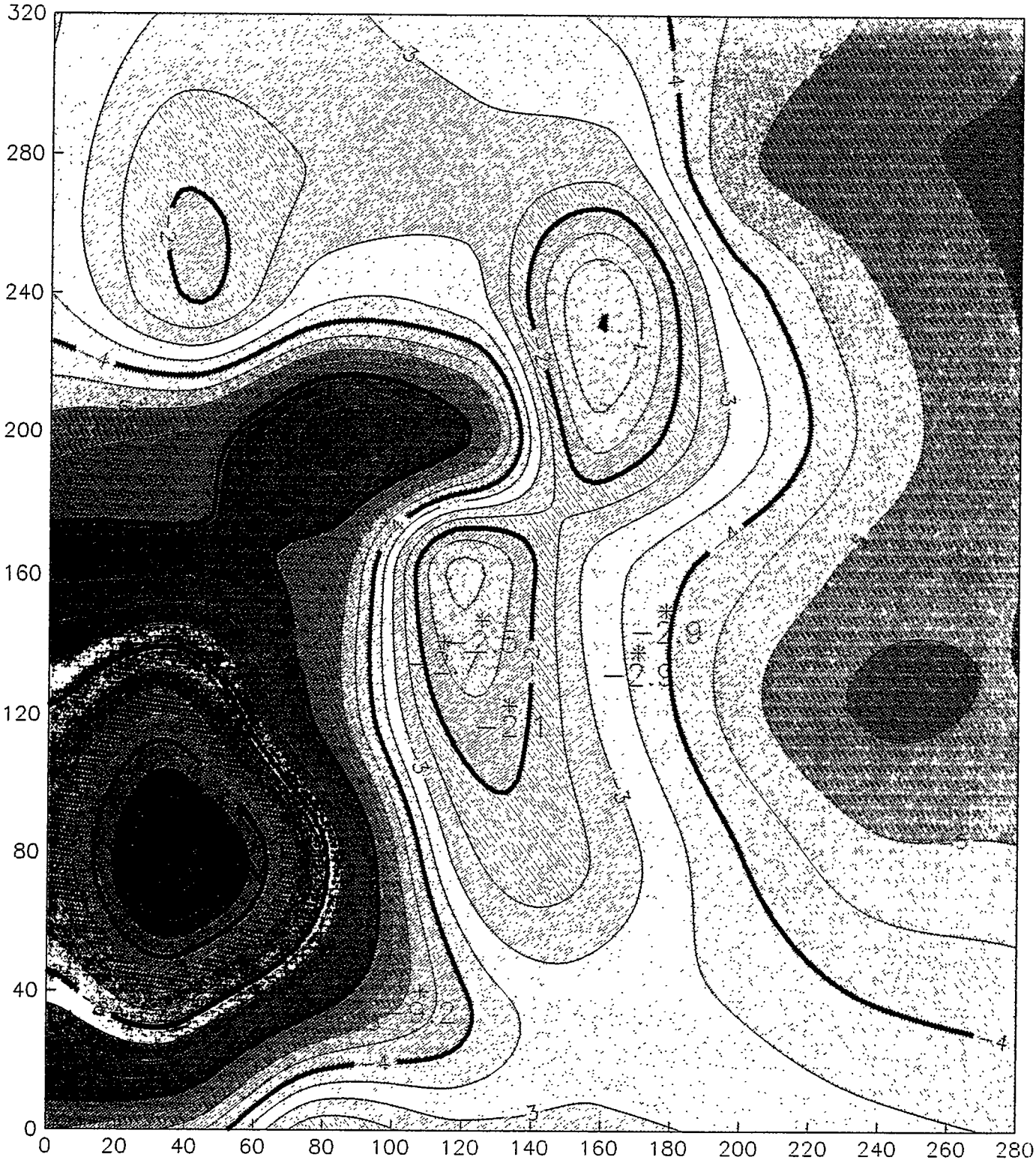

Resistivity Earth Model From Data Fusion
Blair Lakes Target Range, Alaska
Property Color Key
Display: xgrl_param_2.faces
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Z exaggeration: 5.0
Azimuth: 306.8
Inclination: 24.6
X Chair Cut: 0.0
Y Chair Cut: 240.0
300
250
200
150
100
50
0
240
200
150
100
50
0

FIGURE 8. Depth to Top of Permafrost Contour Map
Generated Using Data Fusion

Top of Permafrost From Data Fusion



5.0 CONCLUSIONS AND RECOMMENDATIONS

Although the methodologies of data fusion and RESIX Plus™ are vastly different, the results were generally similar, with a few significant discrepancies.

Using conventional analysis, each resistivity sounding is evaluated separately and requires considerable user-software interaction at almost all stages of the evaluation. Significant user knowledge and interpretation was required to generate and choose the best-fitting and most well-confined (based on equivalence analysis), geologically realistic geoelectric models to pick the top of permafrost.

Using data fusion, however, the only user interaction with the software is to define the initial earth model and its associated statistical parameters (which affect how the data fusion software will vary the earth model), grid size, and measurement sigmas for the entire problem in the input files before the data fusion routine. Once the data fusion process is started, the user has no control over the evaluation process.

In data fusion, all resistivity soundings are treated alike, and they must have the same number of layers as the initial earth model. In general, dc resistivity measurements tend not to be spatially continuous over large areas, especially in the environment where these data were gathered, where permafrost is discontinuous as is the geologic stratigraphy (i.e., lenses and interbeds). To obtain accurate solutions, resistivity measurement data from shorter "a" spacings, representing shallow, thin beds, had to be deleted, and the geoelectric section for every sounding was simplified to a two-layer model. The heterogeneity of the resistivity measurements is probably the reason that data fusion software had difficulty converging on an overall solution.

Using data fusion, there is no software feedback on the fitting errors and equivalence models for each resistivity sounding solution. The dc resistivity method, like other electrical methods (i.e., time-domain electromagnetics), does not have a unique solution. As a result, all possible solutions (geoelectric models in this case), or at least a number of alternative solutions, should be analyzed to determine which model is best (based on a number of factors) and how much the alternative models vary from the chosen best-fit model. Using the conventional approach to this problem, the final models were chosen based on fitting error, variance in equivalence analysis, and geologic accuracy. Model equivalence is not taken into account in the data fusion approach. The differences between the two methods of evaluation may explain why data fusion generated different permafrost top solutions for several of the resistivity soundings.

A cause for concern in the data fusion results is the fact that several of the well picks were not honored (see Figure 6), even if their sigmas were made very small. The resistivity soundings appear to receive more weight than well picks in the data fusion algorithm because every "a" spacing measurement is treated as a separate data point and every resistivity sounding incorporates a large number of data points, while a well pick represents only one data point. Therefore, if a well pick is near a resistivity sounding, the well pick will be made statistically insignificant by the large number of resistivity data points, even though the solution to the resistivity sounding only corresponds to a small area beneath the center of the sounding.

Ideally, every resistivity sounding should be analyzed separately using a conventional evaluation software package to determine how the soundings should be edited and how much variance there is in equivalent solutions before using data fusion. In many cases, data fusion may not be the best method to analyze dc resistivity data (i.e., data fusion cannot converge on a solution). In some ways, evaluating the soundings separately and finding solutions using

the conventional methods before using data fusion defeats the purpose of using data fusion. However, data fusion may be useful for combining dc resistivity data with other data sets obtained using different electrical measurement methods (i.e., time-domain and frequency-domain electromagnetics) to produce a single, best solution. This capability, however, has not been tested yet, and it may run into difficulties because of the nonuniqueness of the measurement solutions.

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