PRELIMINARY THREE-DIMENSIONAL VISUALIZATION OF THE ROTOKAWA GEOTHERMAL FIELD

Topical Report RSI-2081

prepared for

Mighty River Power
Level 14, 23–29 Albert Street
P.O. Box 90399
Auckland, New Zealand

October 2009

RESPEC
CONSULTING & SERVICES

PRELIMINARY THREE-DIMENSIONAL VISUALIZATION OF THE ROTOKAWA GEOTHERMAL FIELD

Topical Report RSI-2081

by

Crystal M. Hocking
Matthew D. Minnick

RESPEC
P.O. Box 725
Rapid City, South Dakota 57709

prepared for

Mighty River Power
Level 14, 23–29 Albert Street
P.O. Box 90399
Auckland, New Zealand

October 2009

TABLE OF CONTENTS

LIST OF TABLES

TABLE **PAGE**

LIST OF FIGURES

1.0 INTRODUCTION

RESPEC was contracted in August 2009 to build a pilot three-dimensional (3D) visualization of the Rotokawa geothermal field and instruct the Mighty River Power (MRP) geoscience staff on the construction process and use of the model. The main objective of the 3D visualization of the Rotokawa geothermal field is to facilitate a better understanding of the spatial distribution of enthalpy in the well field and its association to other parameters, including geology, structure, temperature, flow, and injectivity. Mining Visualization Systems (MVS), by C-TECH Inc., was chosen as the software platform for the geologic modeling and data visualization. MVS is the ideal platform for visualization of the well field with the main objective in mind. MVS allows for modeling of complex geologic structures, including highly faulted systems as found in Rotokawa. The data parameters, including temperature, enthalpy, flow and injectivity, can be interpolated into the geologic framework using 3D geostatisical functions. Once the interpolations are complete, subsetting of the data can be visualized in 3D using user-specified ranges for parameter values. This becomes a powerful tool for answering questions to user-defined problems. The 3D modeling process is explained in detail in this report.

2.0 DATA FORMATTING AND IMPORT

MVS has various file input formats depending on data types, format, and objectives. A few of those formats important to this project are discussed in this report. All data files for MVS can be constructed using a text editor such as Ultra Edit and Microsoft Excel. MVS is not directly database driven, but C-TECH provides a Microsoft Access framework and basic **ArcGIS** tools to help facilitate data storage and input file creation. Small data files, a thousand to a few hundred rows or less, can be easily constructed by hand. Larger data files may require automated data processing for efficiency; this can be accomplished using scripting programs, including **MATLAB** by Mathworks Inc.

The Rotokawa model requires three different file formats, including a pregeology file (pgf) for the geology data from the wells; a 3D chemistry file (csv) for the temperature, enthalpy, flow, and injectivity data; and a geology multifile (gmf) for generated formation surface data. The pgf and gmf can be saved using a text editor as a general file type with the correct suffix (i.e., *.pgf or *.gmf). The 3D chemistry file can be constructed in Excel and saved as a comma-delimited file (i.e., .csv). An example of the pgf is given in Table 2-1. The pgf has three header lines. The first line contains general format data and is the same for all pgfs, the second line specifies whether the *Z* values are depths or in elevation and lists the formation names in order from top to bottom, and the third line contains an integer specifying the number of data lines in the file not including the three header lines. The data lines contain *x*, *y*, and *z*, formation identification and well name. MVS does not directly interpret deviated well data. Values of *x*, *y*, and *z* must be calculated outside MVS for formation contacts and input into the pgf. The formation identification number must start at "0" and increase in consecutive integers up to the number of represented formations. The 3D chemistry file is similar to the pgf, having three header lines and a body of data, as shown in Table 2-2. The first header line contains general format data and a listing of analytes after two @@ characters. In this case, the analytes are data values for temperature, but multiple analytes can be included in the same file. Line two contains a *Z* specifying elevation or depth and units. Line three contains an integer specifying the number of data lines, a second integer specifying the number of analytes, and then analytes units—degrees C in this case. The databody contains the *x*, *y*, and *z* location of the data measurement; the analyte value; and optionally, the well name and top elevation. Table 2-3 is an example of the 3D chemistry file with multiple analytes. The gmf in Table 2-4 is simpler. The gmf contains blocks of data representing *x*, *y*, and *z* points for generating surfaces; in this case, formation contacts. The first line of the gmf contains the spatial unit specified. The second line is repeated for each block of data telling MVS which surface the points belong to, starting at surface "0" and so on. The second line may also contain a surface or formation name in quotes, "Superficial."

The raw data files, pgf, and chemistry csv files can be viewed in 3D using the Post Samples data module. Figures 2-1 and 2-2 show the results from the pgf displaying the well tracks

Table 2-1. MVS File Import Structure, Pregeology File (pgf)

X Y Z Geologic_Unit_Id Bore

Elevation “Superficial” “Huka Formation” “Parariki Breccia” “Oruanui Formation” “Waiora Formation” “Haparangi Rhyolite” “Unnamed Volcaniclastics” “Wairakei Ignimbrite” “Waikora Formation” “Tahorakuri Formation” "Rotokawa Andesite” “Greywacke”

271 1

2787704	6282697	336.901	0	RK1
2787704	6282697	306.901	0	RK1
2787704	6282697	296.901	2	RK1
2787704	6282697	266.901	3	RK1
2787704	6282697	171.901	2	RK1
2787704	6282697	–378.099	4	RK1
2787704	6282697	–742.099	5	RK1
2787704	6282697	–806.099	6	RK1
2787704	6282697	–861.099	5	RK1
2788316	6281821	349.961	0	RK2
2788316	6281821	299.961	0	RK2
2788316	6281821	219.961	2	RK2
2788316	6281821	84.961	1	RK2
2788316	6281821	–120.039	4	RK2
2788316	6281821	–530.09	5	RK2
2788019	6281528	339.626	0	RK3
2788019	6281528	309.626	0	RK3
2788019	6281528	219.626	2	RK3
2788019	6281528	69.626	1	RK3
2788019	6281528	34.626	2	RK3
2788019	6281528	–115.374	4	RK3
2788019	6281528	–565.374	5	RK3
2788019	6281528	–571.374	4	RK3
2788808	6282173	350.772	0	RK4
2788808	6282173	340.772	0	RK4
2788808	6282173	310.772	3	RK4
2788808	6282173	90.772	2	RK4
2788808	6282173	–97.228	4	RK4
2788808	6282173	–649.228	5	RK4
2788808	6282173	–984.228	7	RK4
2788808	6282173	–1849.23	10	RK4
2788808	6282173	–2220.23	11	RK4

and geology contacts in 3D. The well deviations are apparent in this visualization with the colors representing the different formations. The temperature, infectivity, flow, and enthalpy data can be displayed using the Post Samples data module, as in Figures 2-3, 2-4, 2-5, and 2-6. Intervals with missing data points along the well are represented with a gray tube displaying the well tract.

Table 2-2. MVS File Import Structure, 3D Chemistry File (csv)

X (Elevation)	Y (Meters)	Elevation	@@Temperature		
370	1	C			
2787703	6282696	233.11	145	RK1	336.901
2787703	6282696	183.11	178	RK1	336.901
2787703	6282696	133.11	195	RK1	336.901
2787703	6282696	33.11	217	RK1	336.901
2787703	6282696	–66.89	208	RK1	336.901
2787703	6282696	–166.89	195	RK1	336.901
2787703	6282696	–266.89	220	RK1	336.901
2787703	6282696	–366.89	250	RK1	336.901
2787703	6282696	–466.89	270	RK1	336.901
2787703	6282696	–566.89	285	RK1	336.901
2787703	6282696	–666.89	292	RK1	336.901
2787703	6282696	–766.89	305	RK1	336.901
2787703	6282696	–866.89	306	RK1	336.901
2788316	6281821	283.68	85	RK2	349.961
2788316	6281821	222.68	140	RK2	349.961
2788316	6281821	161.68	180	RK2	349.961
2788316	6281821	100.68	190	RK2	349.961
2788316	6281821	–20.32	220	RK2	349.961
2788316	6281821	–81.32	222	RK2	349.961
2788316	6281821	–143.32	180	RK2	349.961
2788316	6281821	–205.32	188	RK2	349.961
2788316	6281821	–265.32	205	RK2	349.961
2788316	6281821	–325.32	230	RK2	349.961
2788316	6281821	–387.32	250	RK2	349.961
2788316	6281821	–447.32	270	RK2	349.961
2788316	6281821	–508.32	285	RK2	349.961

Table 2-3. MVS File Import Structure, 3D Chemistry File (csv) With Multiple Analytes

X (Elevation)	Y (meters)	Z	@@ Injectivity Flow Enthalpy				
299	3	t/hb	t/h	kJ/kg			
2786726	6282148	–1398.1	9	30	1130	RK18	330.5
2786724	6282144	–1407.79	9	30	1130	RK18	330.5
2786722	6282140	–1417.96	9	30	1130	RK18	330.5
2786721	6282137	–1428.13	9	30	1130	RK18	330.5
2786719	6282133	–1438.3	9	30	1130	RK18	330.5
2786717	6282129	–1448.47	9	30	1130	RK18	330.5
2786715	6282126	–1457.72	9	30	1130	RK18	330.5
2786714	6282122	–1467.93	9	30	1130	RK18	330.5
2786712	6282118	–1478.15	9	30	1130	RK18	330.5
2786710	6282114	–1488.37	9	30	1130	RK18	330.5
2786709	6282111	–1497.66	9	30	1130	RK18	330.5
2786707	6282107	–1507.87	9	30	1130	RK18	330.5
2786706	6282104	–1518.09	9	30	1130	RK18	330.5
2786704	6282100	–1528.31	9	30	1130	RK18	330.5
2786702	6282096	–1537.59	9	30	1130	RK18	330.5
2786701	6282093	–1547.81	9	30	1130	RK18	330.5
2786699	6282089	–1558.03	9	30	1130	RK18	330.5
2786697	6282085	–1569.6	9	30	1130	RK18	330.5

Table 2-4. MVS File Import Structure, Geology Multifile (gmf)

Units Meters

Surface 0 "**Superficial**"

2787704	6282697	336.901	RK1
2787779	6282804	331.717	RK11
2787839	6282854	328.924	RK12
2788244	6283400	322.0502	RK13
2787900	6283324	321.6501	RK14
2787885	6283322	320.034	RK15
2786861	6282618	330.5	RK16
2786862	6282625	331	RK17
2786862	6282632	331	RK18
2789748	6283632	315.0001	RK19
2789748	6283632	315.0001	RK19ST
2788316	6281821	349.961	RK2
2789343	6282546	346.7	RK20
2788726	6281445	393.64	RK21
2788725	6281458	393.64	RK22
2789356	6282541	346.7	RK23
2789369	6282536	346.7	RK24
2788432	6283867	310.94	RK25
2787132	6283034	326.27	RK26
2786871	6282644	328.67	RK27
2788019	6281528	339.626	RK3
2788808	6282173	350.772	RK4
2788263	6283379	320	RK5
2788242	6284419	325.681	RK6
2787509	6285342	445.48	RK8
2787885	6283387	321.6	RK9

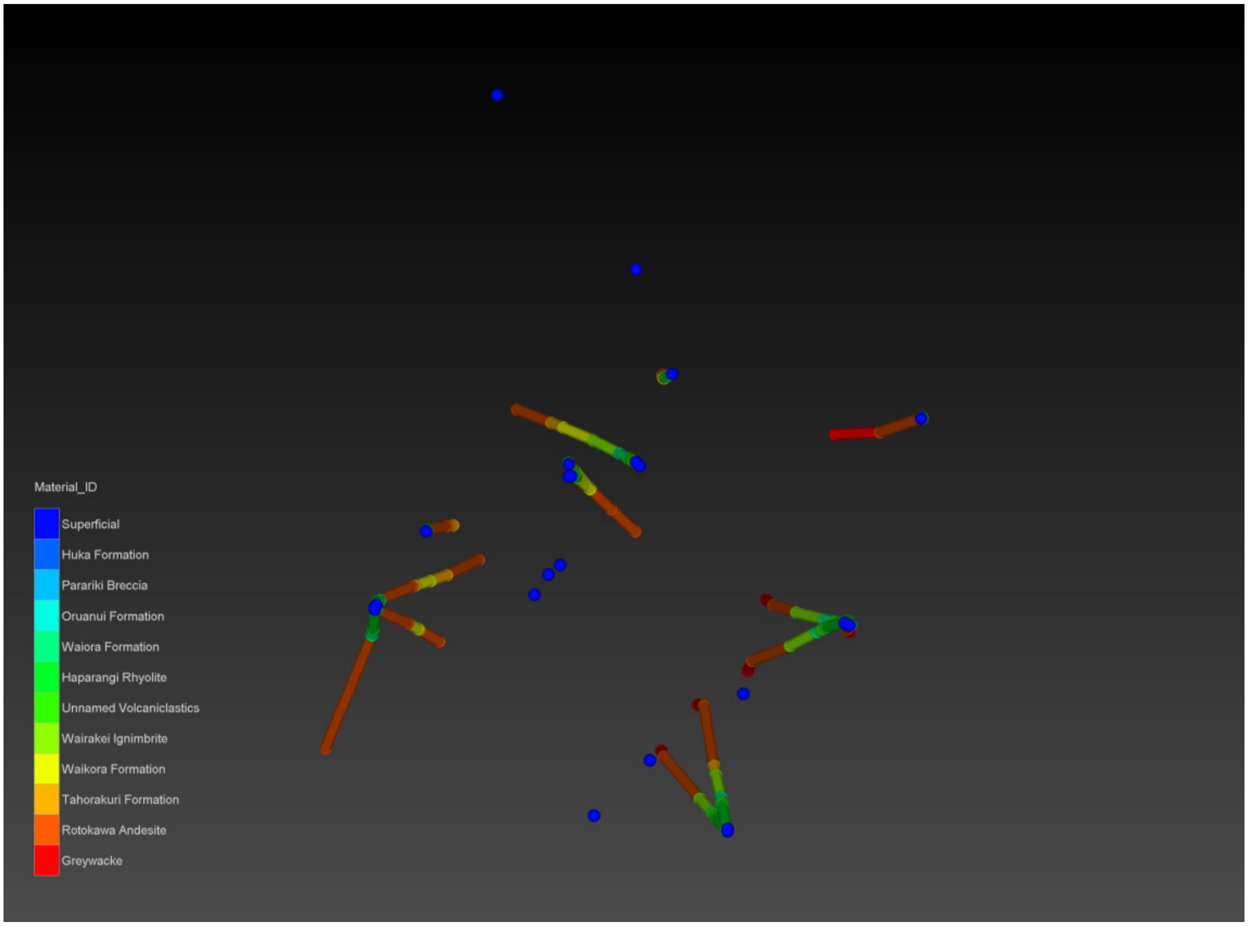

Figure 2-1. Top View of the Well Geology Data in MVS Using the Post Samples Module.

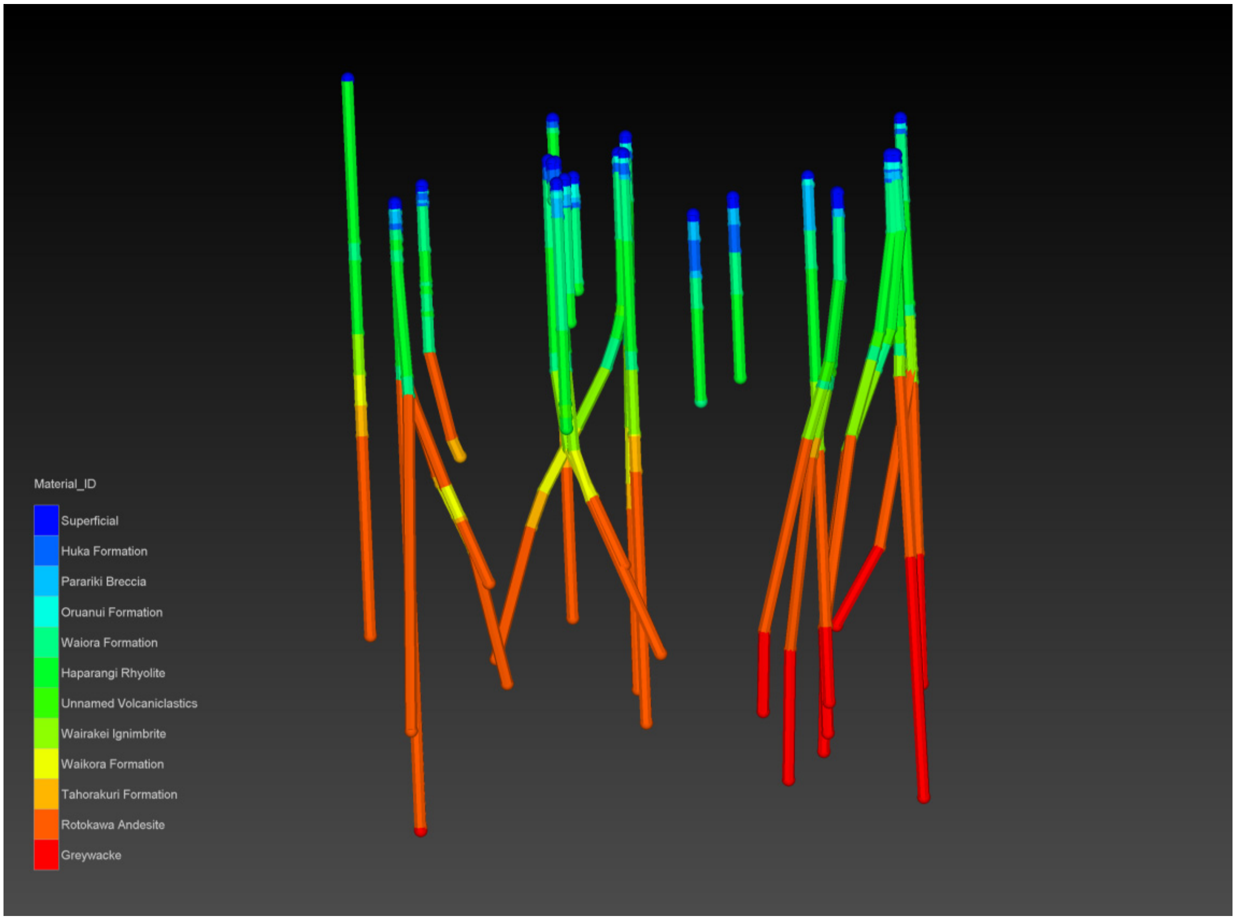

Figure 2-2. Subsurface Side View of the Well Geology Data in MVS Using the Post Samples Module. The deviation of the wellbores is easily visualized in this form.

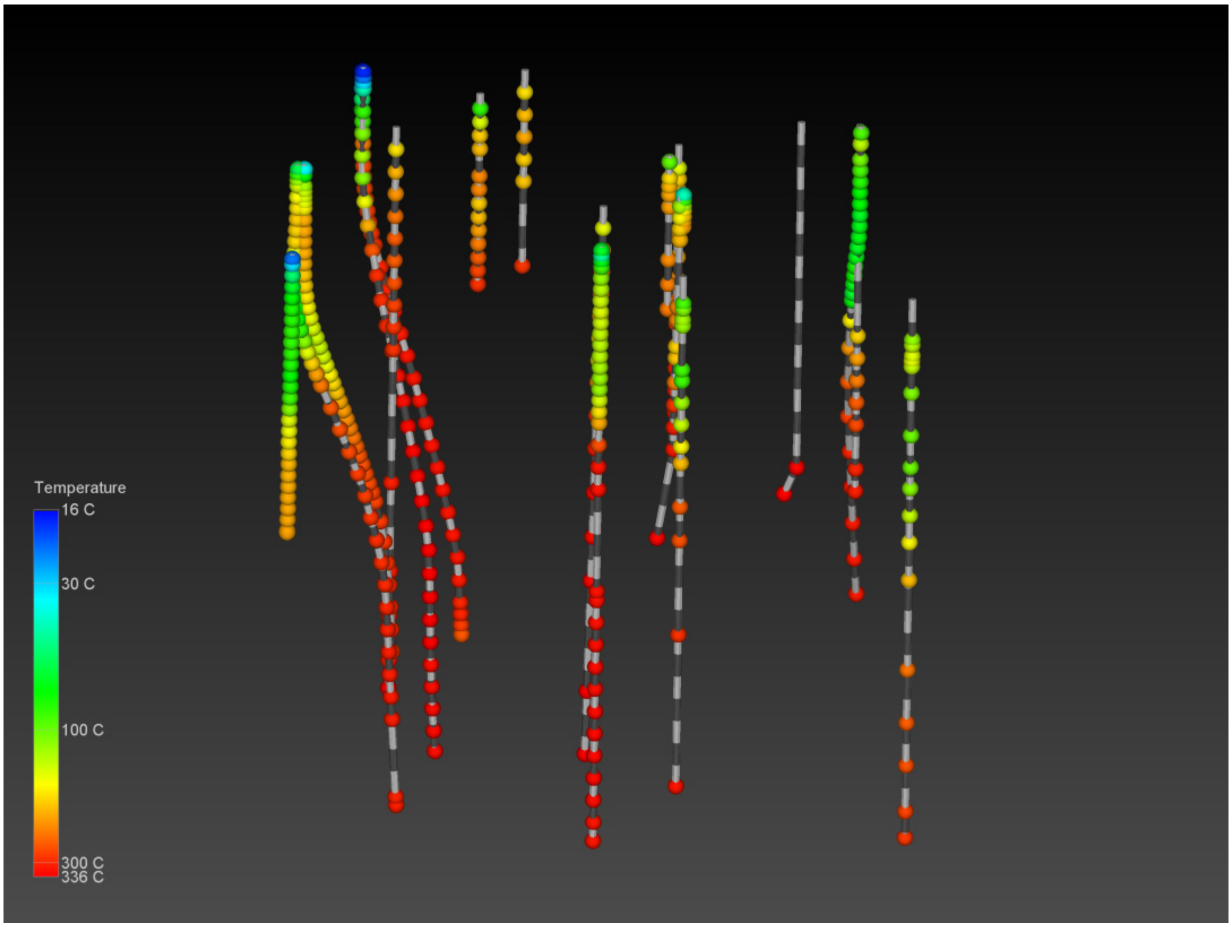

Figure 2-3. Visualization of the Well Temperature Data Using Post Samples.

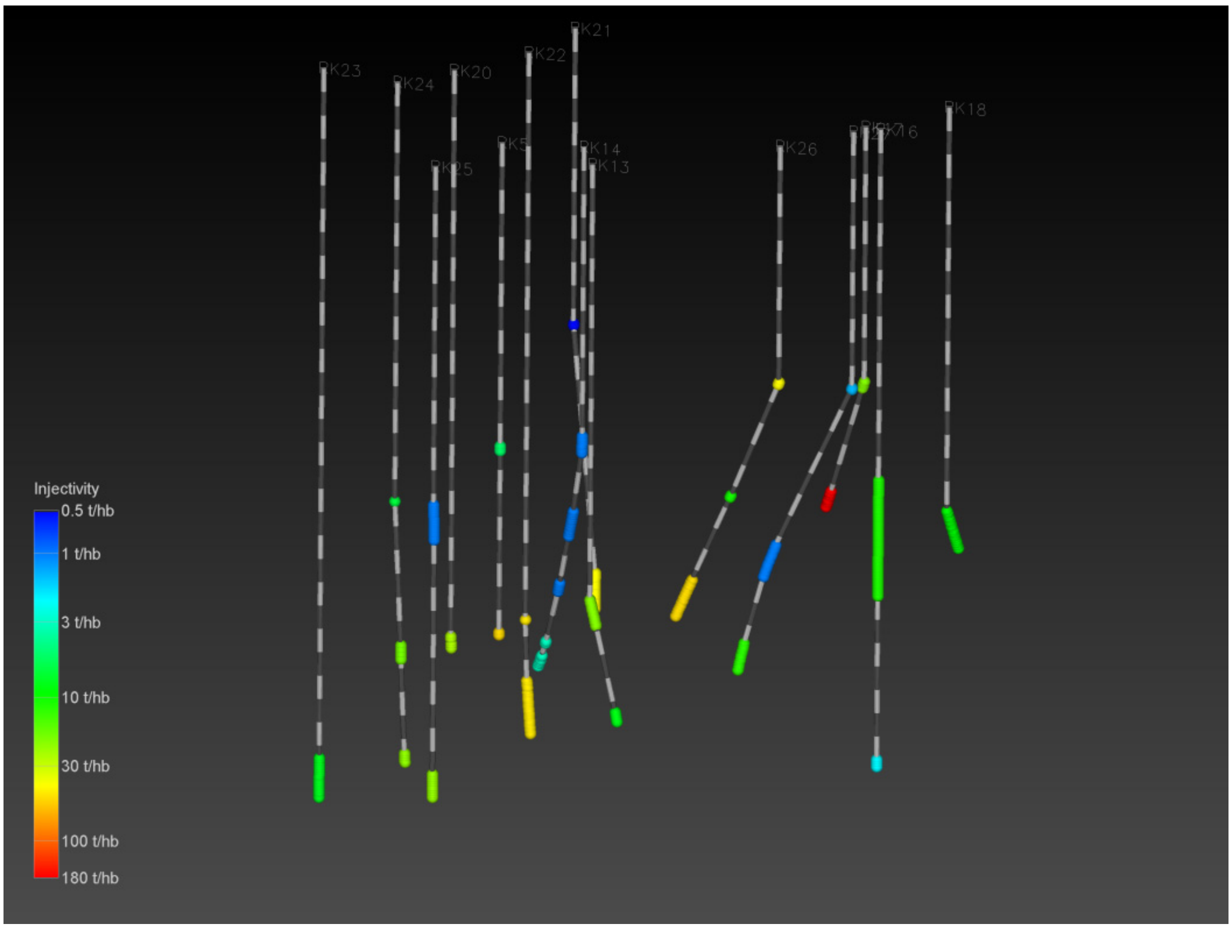

Figure 2-4. Visualization of the Well Injectivity Data Using Post Samples. Intervals with missing data is represented in gray showing the well tracts.

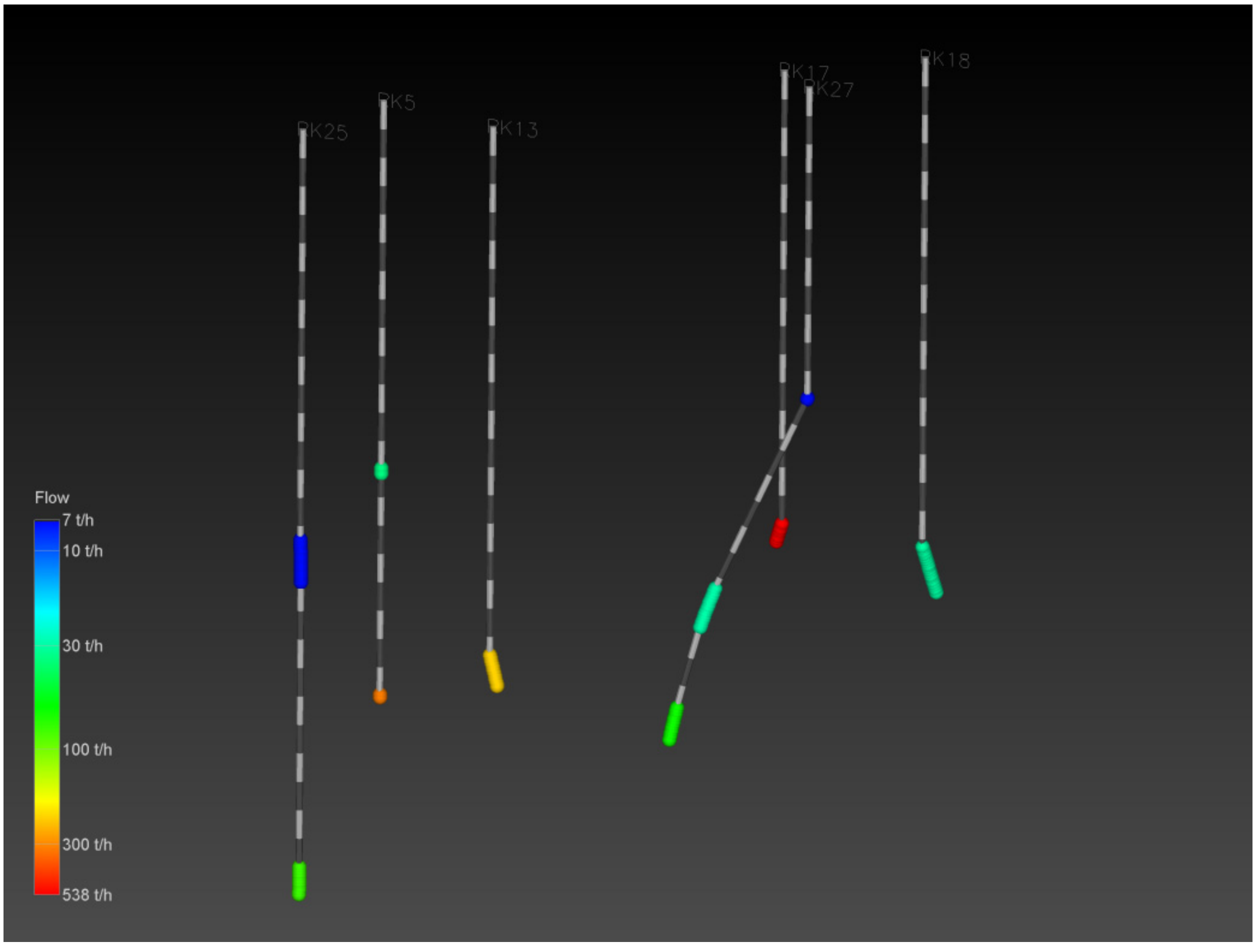

Figure 2-5. Visualization of the Well Flow Data Using Post Samples.

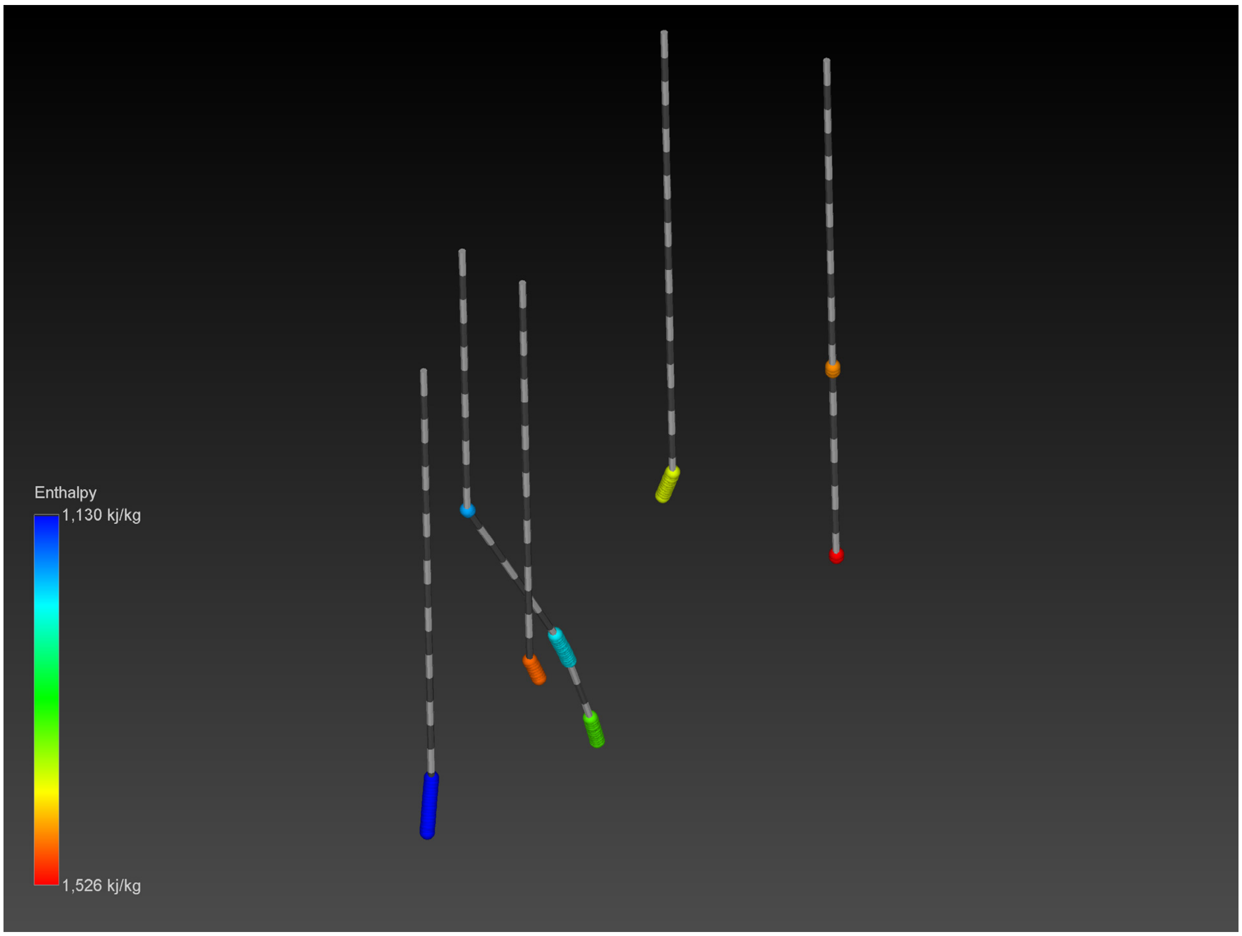

Figure 2-6. Visualization of the Well Enthlapy Data Using Post Samples.

3.0 GEOLOGIC MODEL INTERPOLATION

There are two main interpolation methods used to build a geologic framework in MVS: geo-indicator kriging and the geo hierarchy method. There are pros and cons to each method. For a first run interpolation of the geologic data, geo-indicator kriging works as a quick method to construct a 3D block model of Rotokawa, as shown in Figure 3-1. The geo-indicator kriging module reads in the pgf and uses geostatistical methods to calculate the probability of each cell being a certain material. The material with the highest probability for that cell is then assigned to that cell. This method results in a blocky model; the block size is based on the input size of the interpolation grid specified by the user. The geologic formations can be extracted to display separately, as in Figure 3-2, with the Rotokawa Andesite. The pros of this method include speed of initial interpolation, the ability to fairly accurately model spatial distribution of the rock types and probability of formation assignment, and the ability to interpolate other data into the framework for further subsetting. The cons of this technique are the inability to model faulted layers and explode the model for visualization.

The geo hierarchy geologic model construction uses the gmf format to interpolate surfaces that form contacts for the geologic formations. The space in between the surfaces are filled to form solid formation models. One of the major pros to the geo hierarchy model is the ability to model faulted structures and explode the model along fault surfaces and geologic contacts. Complex stratigraphy with lenses and pinch outs can also be modeled. One of the cons of this method is the complication and added time it takes to get a working geologic framework.

There are multiple ways to set up a geo hierarchy geologic model. The gmf provides the data input to interpolate the formation contact surfaces. The gmf needs to be built from the pgf either by hand or through an automated process using the geo hierarchy module in MVS. In the case of the Rotokawa geothermal field, the MVS module for automating the construction of the gmf is only partially useful because the module does not handle faulted structures. For our purposes, the geo hierarchy module was used to generate the gmf surface data blocks for the upper formations that have not experienced faulting. To accurately model the faulted formations and blocks, multiple gmfs must be made to generate the surfaces for each block of the model separated by the faults. These gmfs can be built manually by taking the top surfaces data blocks created from the geo hierarchy module and adding data points for the faulted surfaces from the pgf. Each of these manually built gmfs can then be input into separate 3D Krige Geology modules to generate surfaces and then passed through the 3D Geology Map module to create the solid formation bodies. In the case of the Rotokawa geothermal field, seven separate gmfs were created to represent different blocks bounded by the faults. To bound the seven blocks, the output from the 3D Geology Map module must be run through a Surf Cut module. The Surf Cut module takes the 3D block and cuts it by an input surface, which in this case, are generated fault surfaces. The fault surfaces for this model were made two ways. The

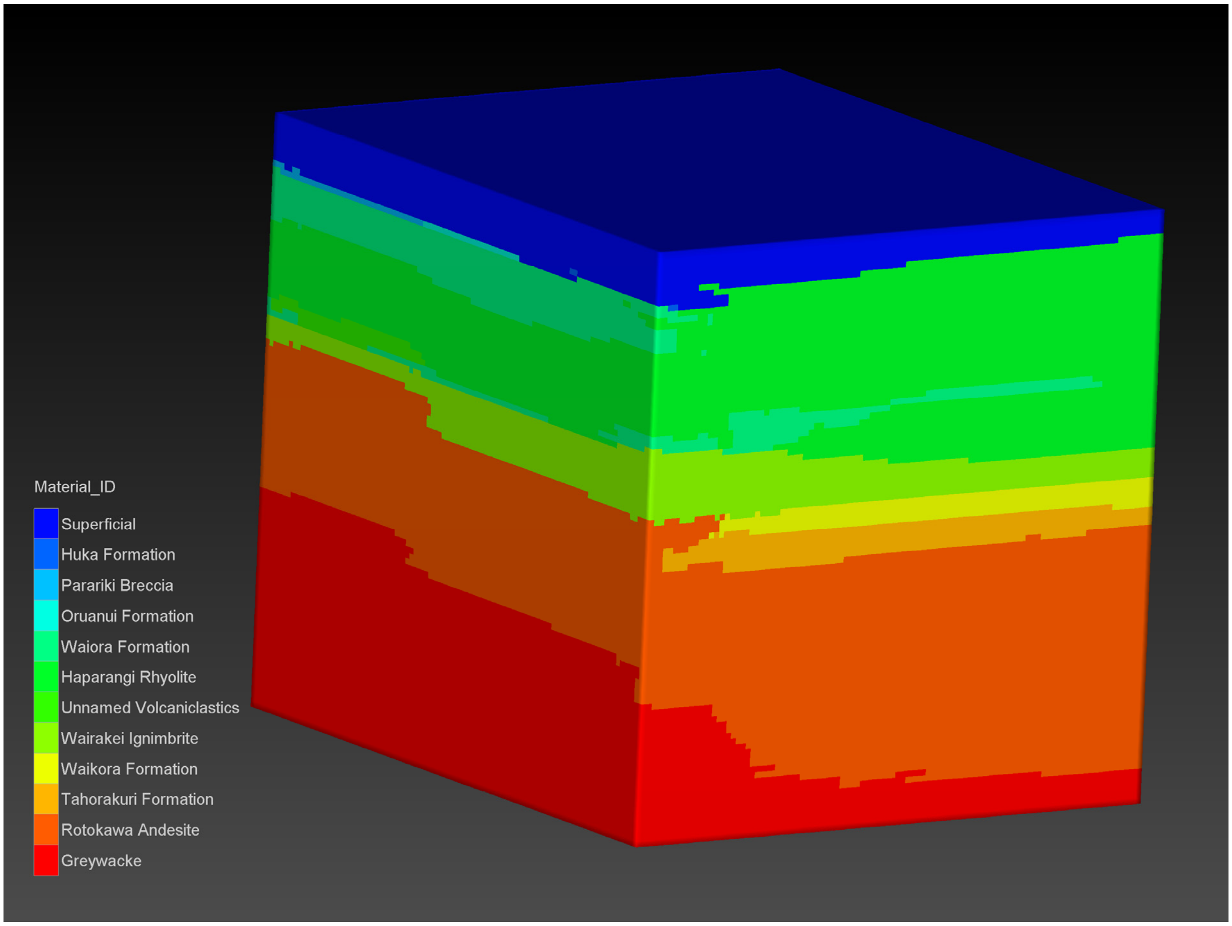

Figure 3-1. Geologic Model Created by the Geo-Indicator Kriging Method.

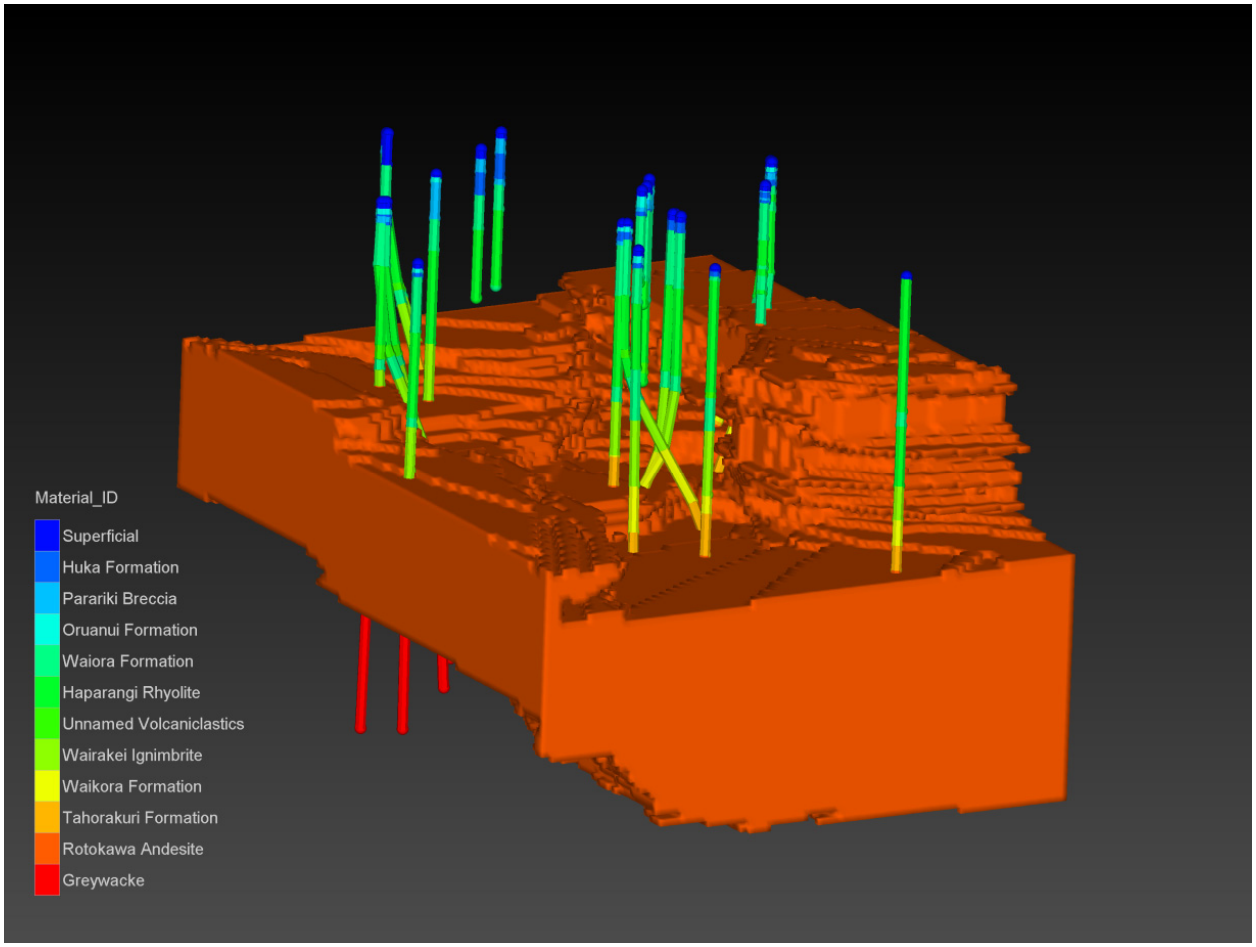

Figure 3-2. A Geo-Indicator Interpolated Geologic Model Subset to Show the Spatial Distribution Rotokawa Andesite.

first way used the Create Fault Surface module that allows the user to construct an orientated plane representing the fault surface. The plane orientation is interactively adjusted to fit offsets visually recognized in the well data. Once an acceptable plane has been established using the Create Fault Surface module, the plane can be saved as an MVS file for use as input into the Surf Cut module. The one curved fault surface need for Rotokawa must be made by constructing a single surface gmf by hand, estimating x, y, and z points that would form the basis for interpolating that fault plane. The cut blocks can then be combined together via the merge fields modules and saved as one complete model for use in subsetting and as a framework to interpolate other data into. Figure 3-3 shows the network of modules used to create the Rotokawa geologic faulted model. The final faulted model is presented in Figure 3-4 and exploded in Figure 3-5. Figure 3-6 shows the removal of nonfaulted layers from the block module, and Figure 3-7 presents north- and south-trending cross sections cut through the faulted model.

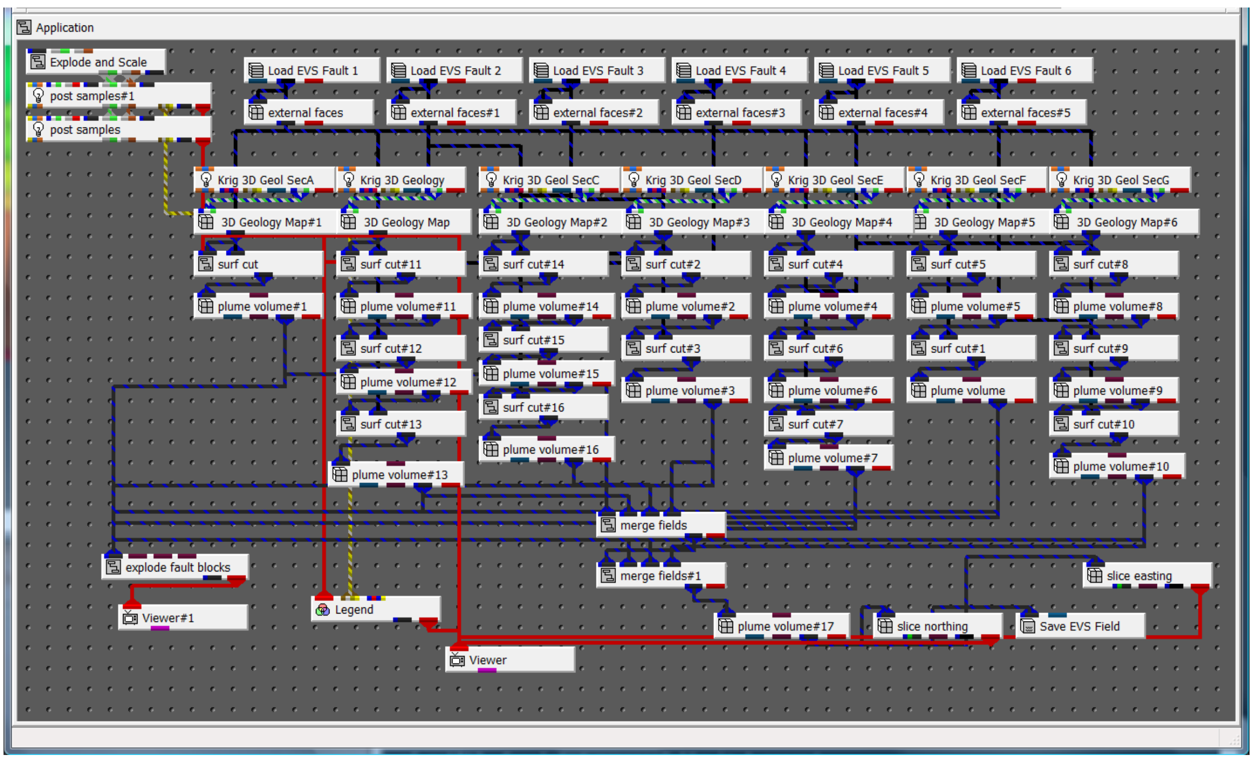

Figure 3-3. Layout of Module Structure Used to Create the Faulted Model.

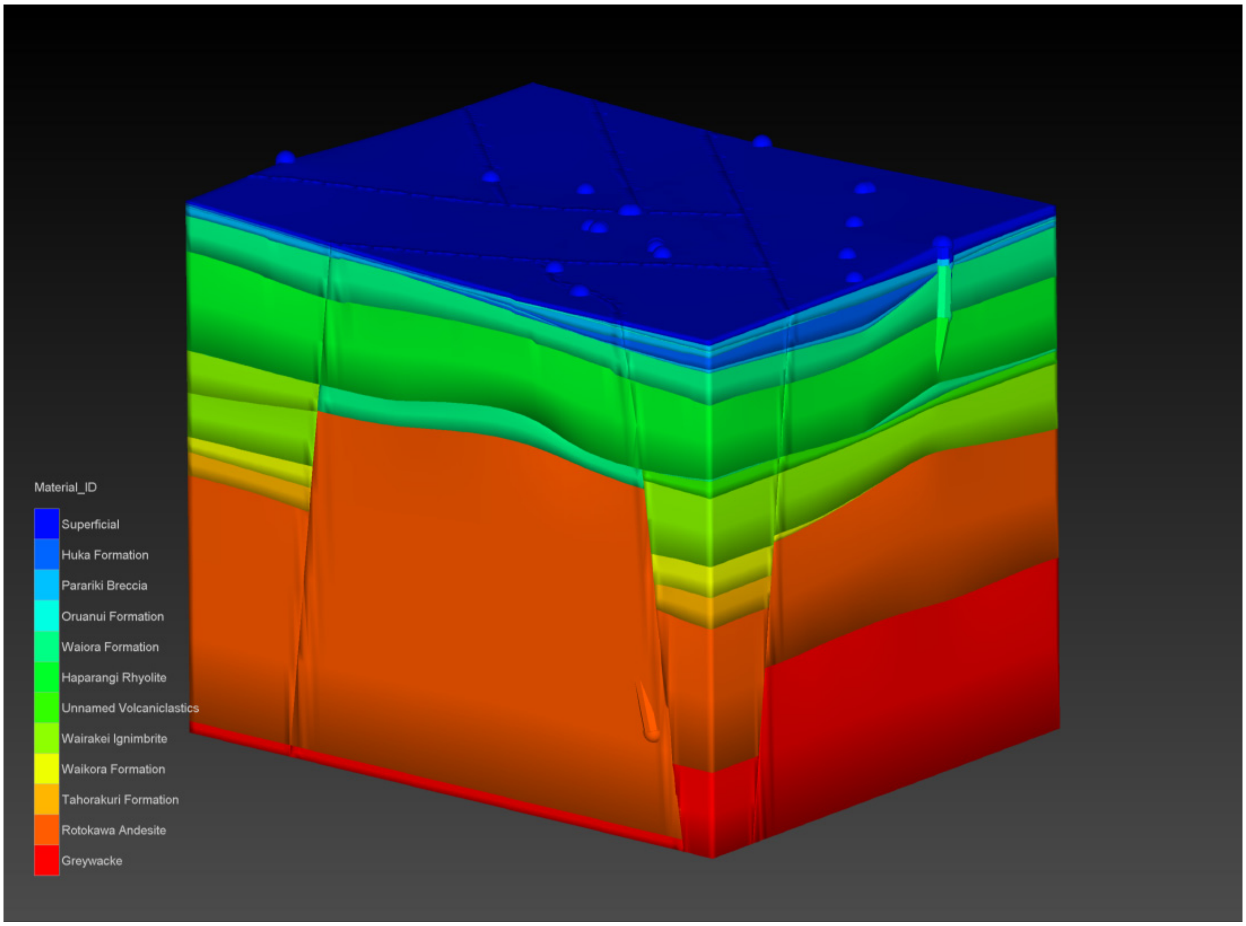

Figure 3-4. Faulted Block Model Created Using Interpolated Surfaces.

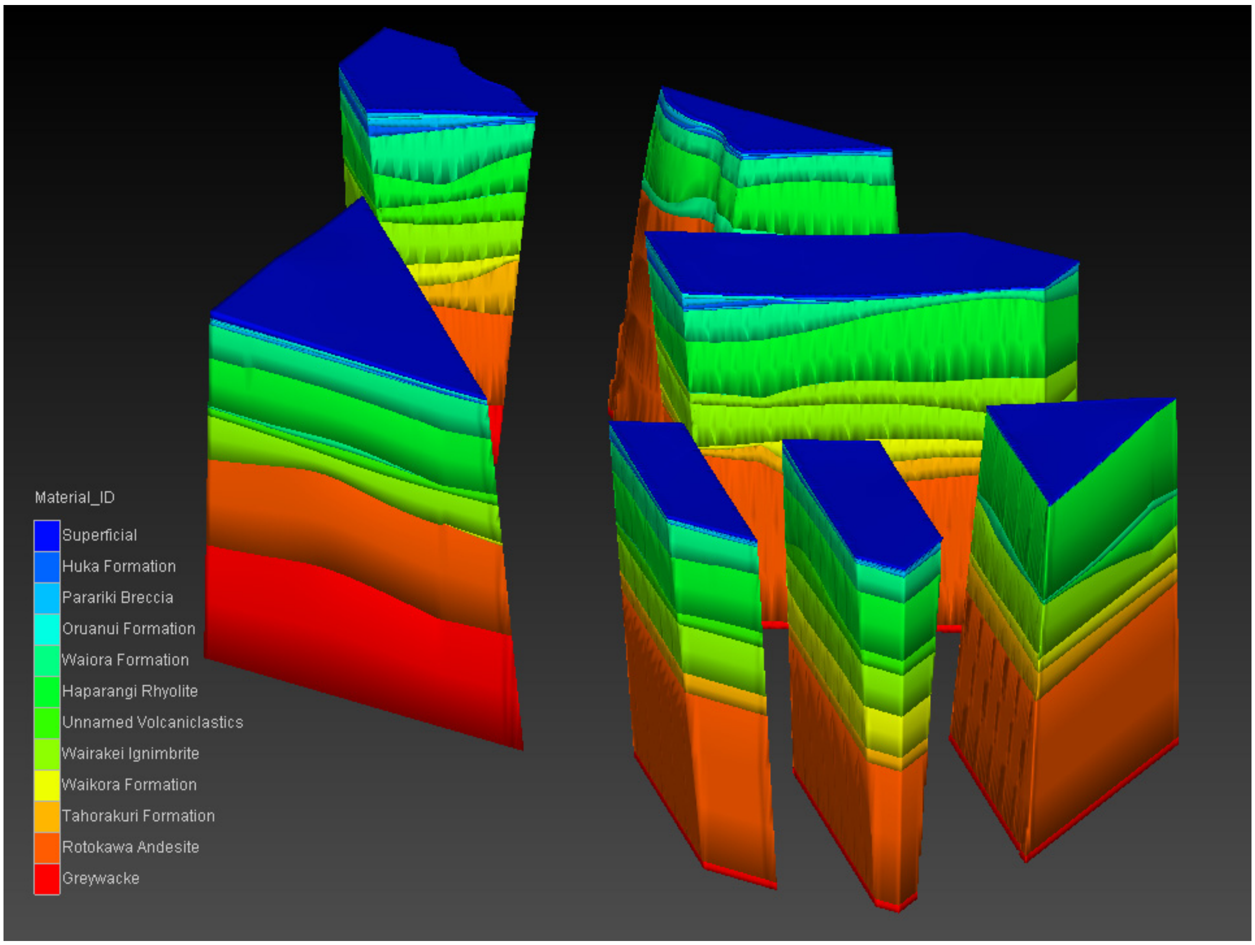

Figure 3-5. Exploded Visualization of Faulted Block Model. Formations above the true faulted formations are broken apart along extended fault surfaces to create visualization. These shallower formations are not faulted and offset but continuous, as seen in Figure 3-4.

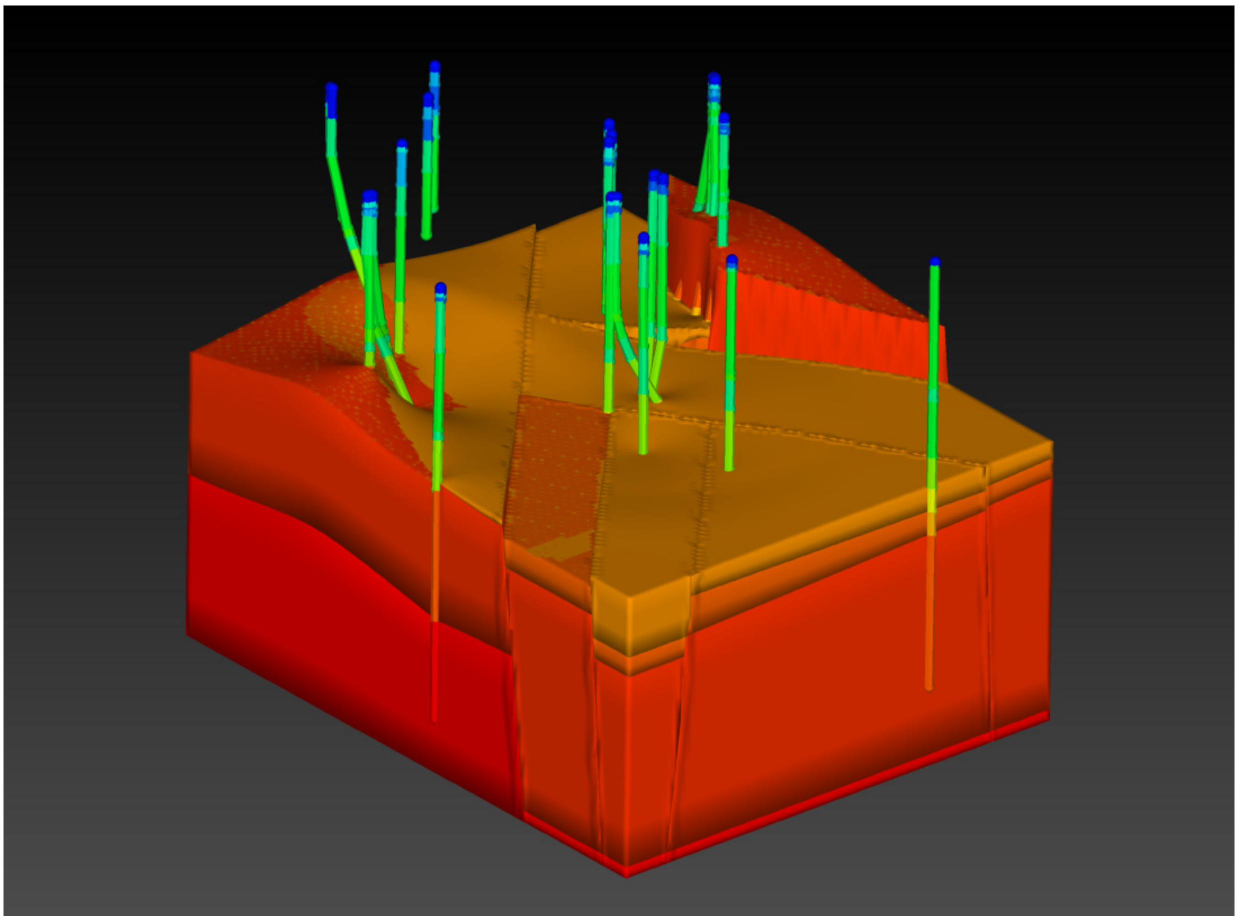

Figure 3-6. View of Faulted Block Model With the Continuous Nonfaulted Layers Removed.

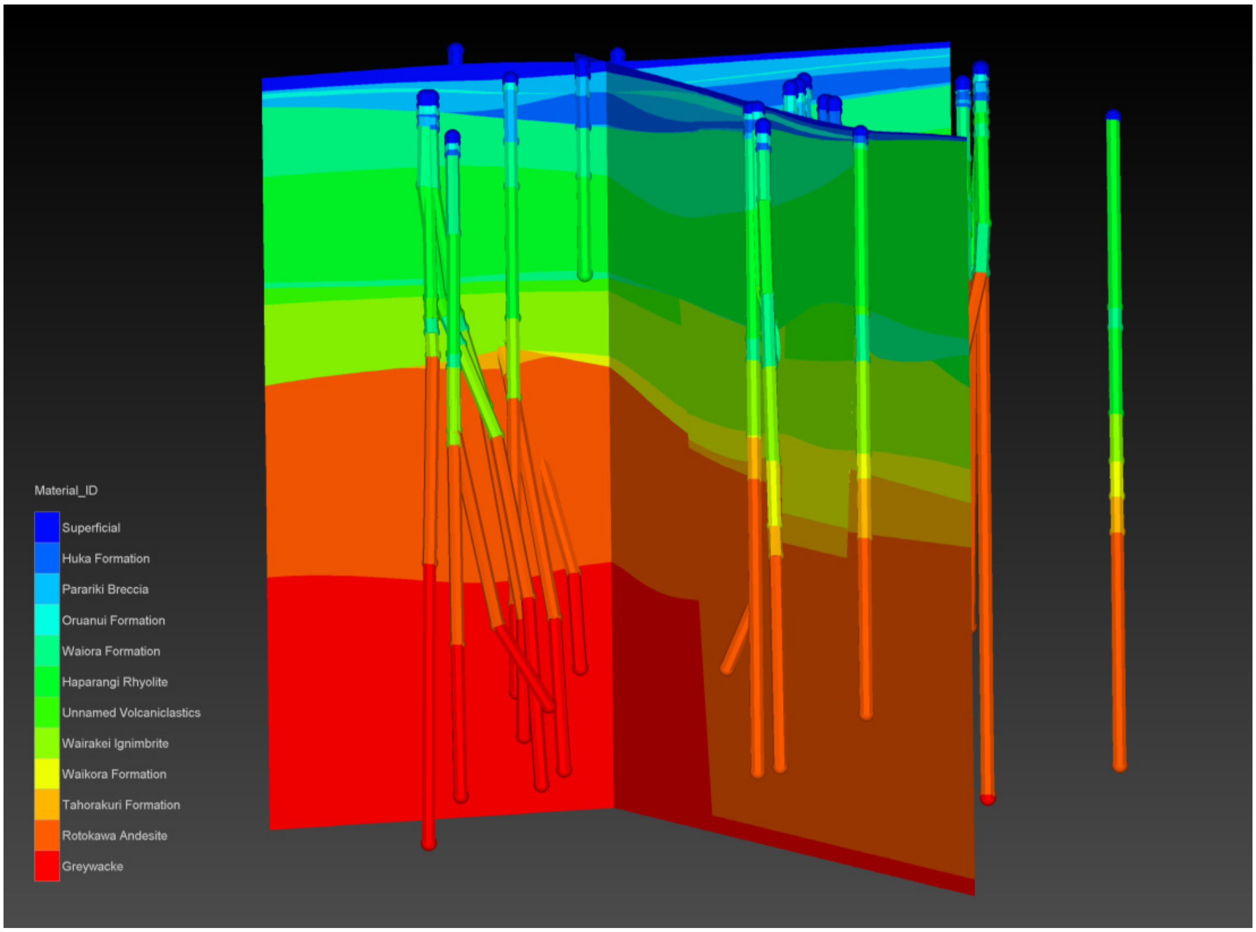

Figure 3-7. North- and South-Trending Cross Sections Through Faulted Block Model.

4.0 WELL PROPERTIES DATA INTERPOLATION

The temperature, flow, injectivity, and enthalpy measurements taken in the wells can be displayed as data points along the well tracts but can also be interpolated into the geologic framework. Interpolating this data in 3D adds the analytes to the nodes that form the geologic framework that provides the user the ability to do more advanced subsetting and volume calculations. Figure 4-1 shows the result of interpolating the temperature data into the faulted geologic model. To accomplish this, the faulted geologic model can be loaded using the Load EVS field module and the framework linked to the input port of the Krig_3D module. The Krig_3D module is then used to load the 3D chemistry files containing the target data. The gridding properties of the module are then set by the geologic model framework. The geostatistical method for performing the 3D interpolation of the data can be set in the Kriging parameters window. There are multiple interpolation algorithms offered, including a statistical kriging, min-max, inverse distance weighting, and nearest neighbor. Kriging with statistical output was chosen for this interpolation to help optimize the use of the sparse dataset. There are multiple parameters under this interpolation option that can be set to optimize the interpolation. In this case, it is important to check the box that allows the use of all the data points in calculating the node values because of the small dataset. The parameters can be left with default values or modified to induce different outcomes in the interpolation. It is generally good to leave the default parameters MVS calculates from reading the dataset and spatial distribution for the first interpolation run. If the results are not satisfactory, then other parameters can be changed, including the kriging semivariogram. Results for interpolating flow, injectivity, and enthalpy are shown in north and south cross sections in Figures 4-2 through 4-4.

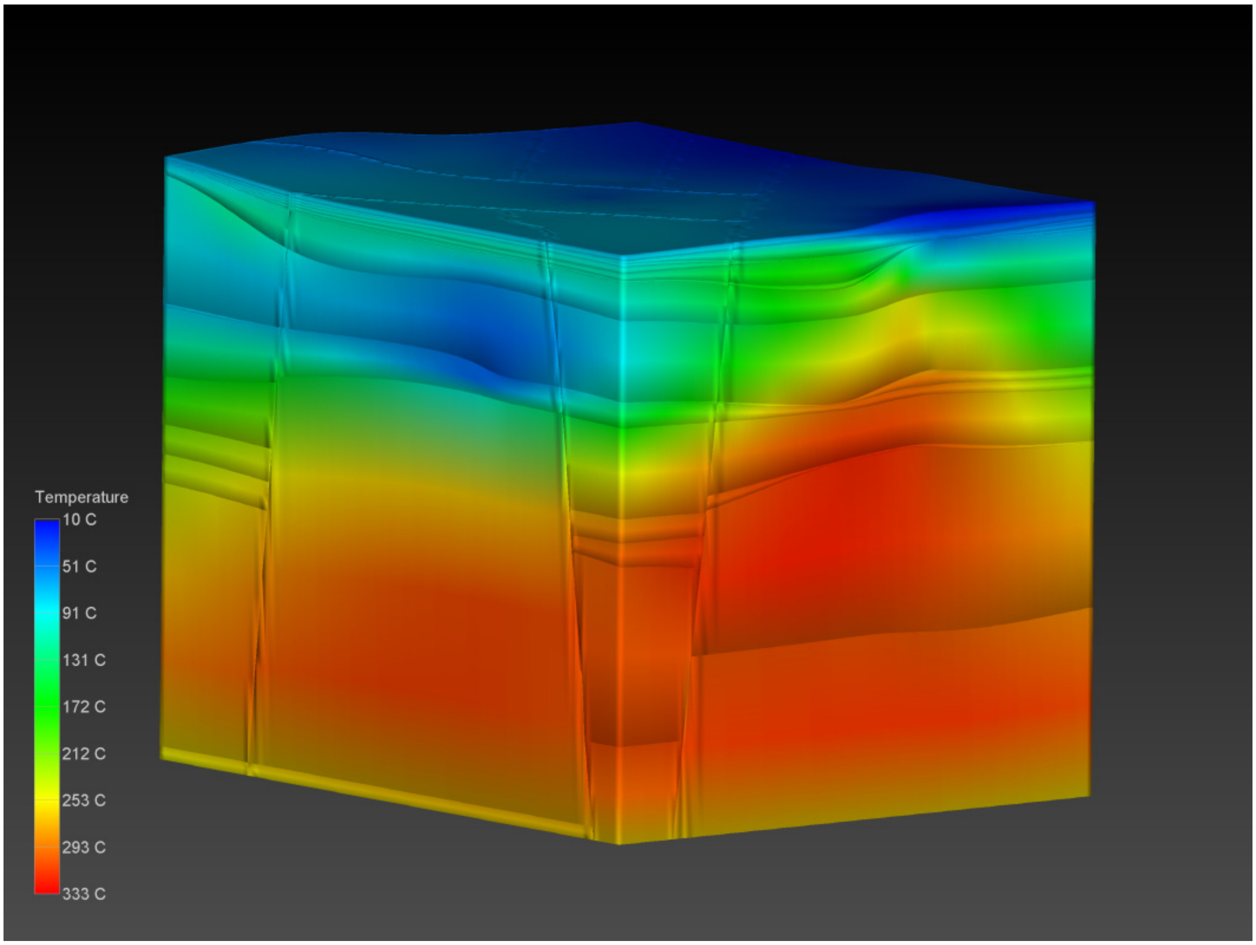

Figure 4-1. Interpolation of the Temperature Data Into the Faulted Block Geologic Model.

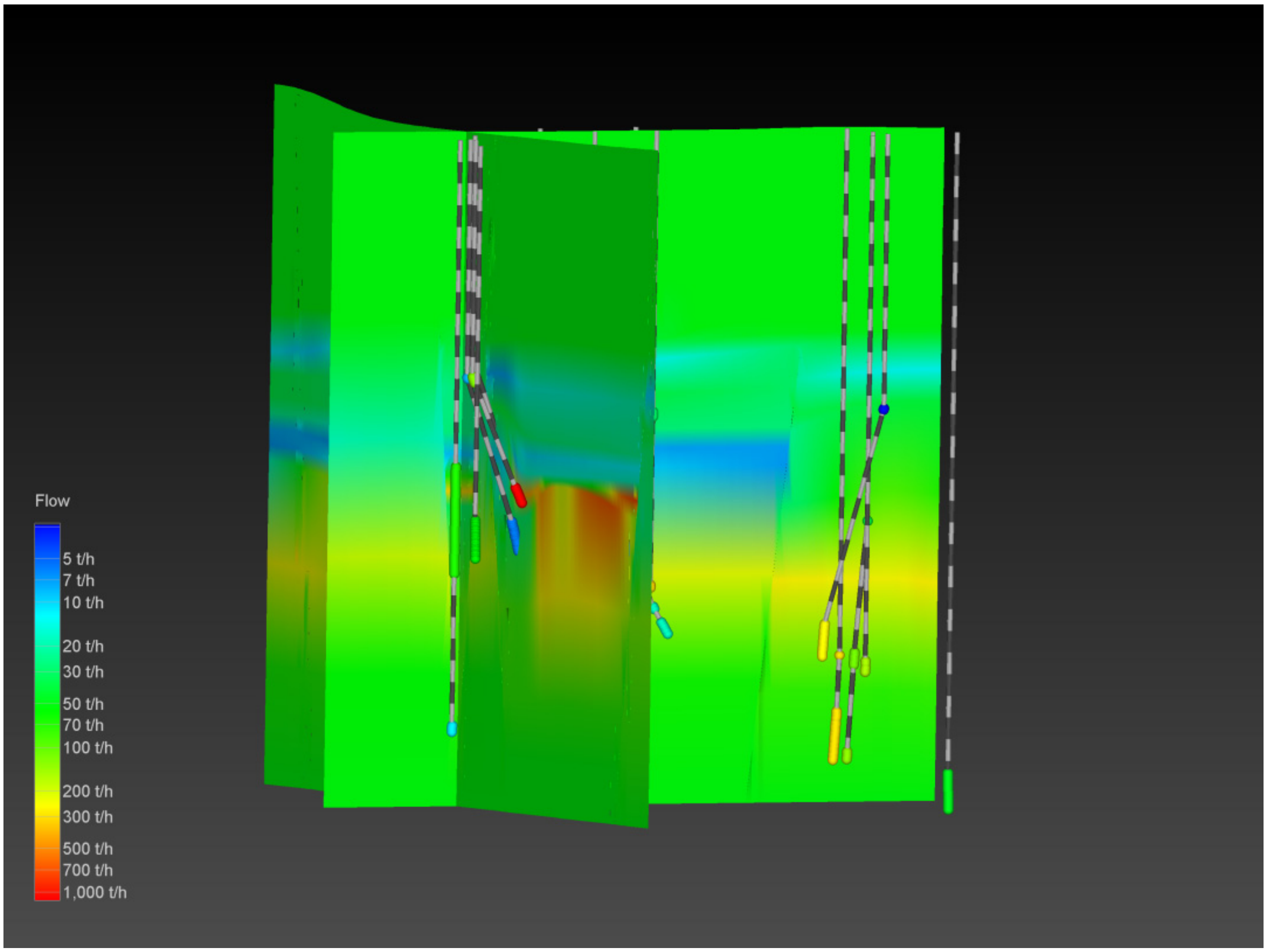

Figure 4-2. North and South Cross Sections Through Flow Data Interpolated Into the Faulted Geologic Model.

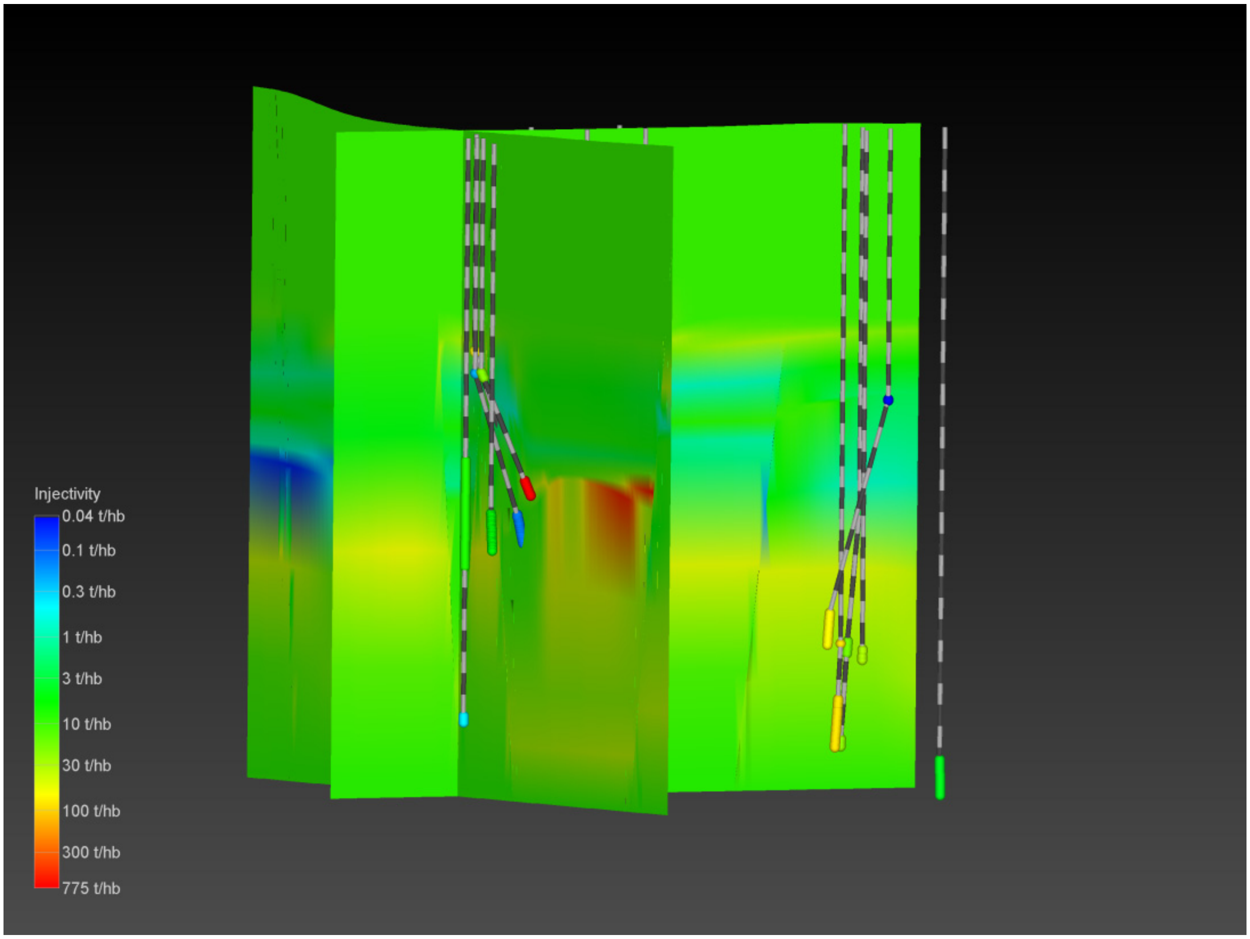

Figure 4-3. North and South Cross Sections Through Injectivity Data Interpolated Into the Faulted Geologic Model.

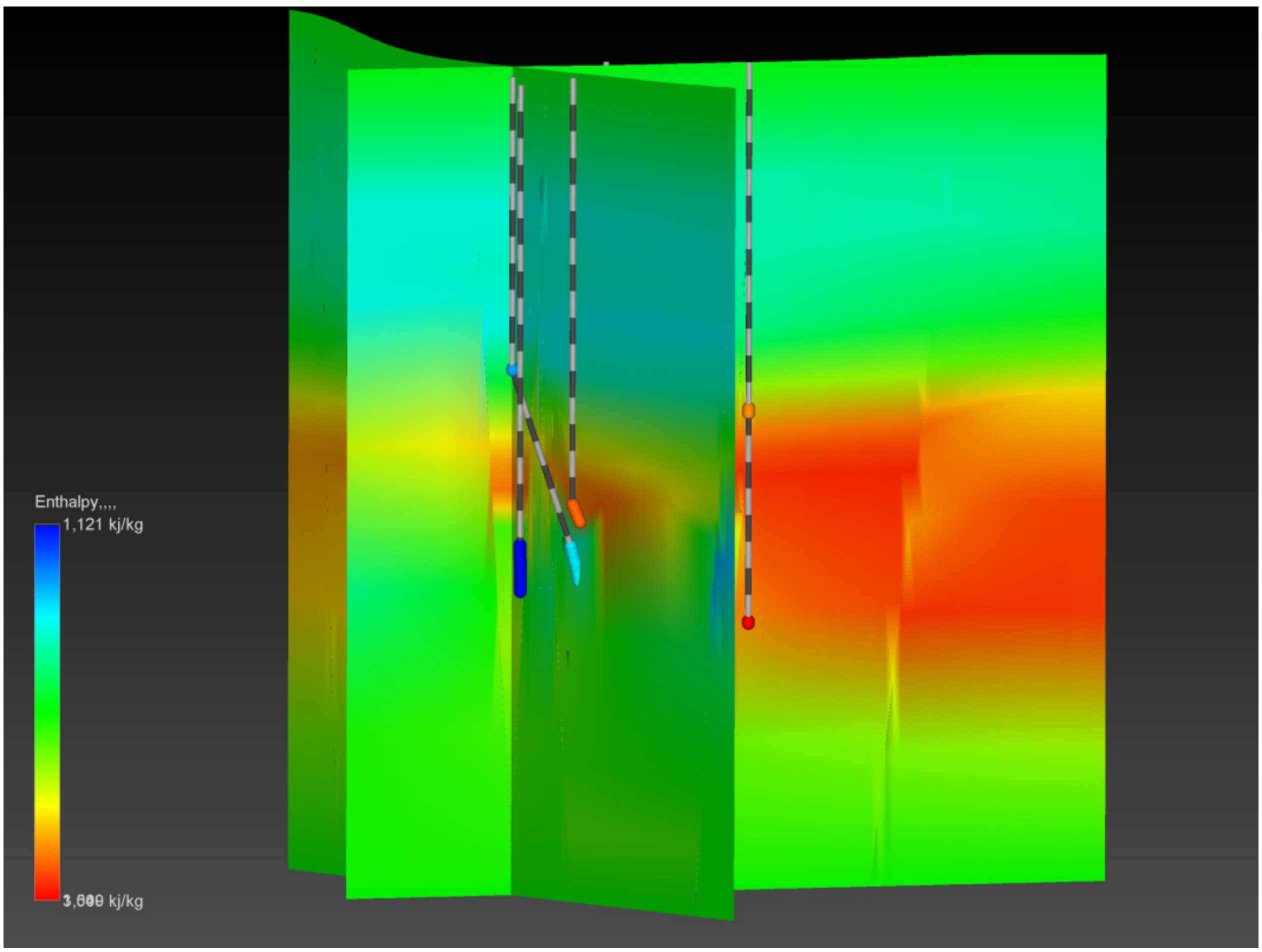

Figure 4-4. North and South Cross Sections Through Enthalpy Data Interpolated Into the Faulted Geologic Model.

5.0 VISUALIZATION

A core component of the MVS system is the powerful subsetting features and animation generation. The Plume Volume module allows for subsetting the completed model by querying various data components assigned to the model nodes. Any of the attributes, including geologic formation, temperature, flow, injectivity, enthalpy, and statistics calculated for each, can be used to select portions of the model and view the spatial distribution of these attributes. This may be done on multiple components by linking together multiple Plume Volume modules as demonstrated in Figure 5-1 where the spatial distribution of the geology is shown with enthalpy values above 1,400 kilojoules/kilogram (kJ/kg). MVS also provides utilities to create animation files, which are very useful in conveying results of the model in 3D without running the MVS program. A partially interactive 3D animation can be constructed using the Record_4DIM module. The resulting .4d file can be viewed through a freely distributed 4 DIM model viewer.

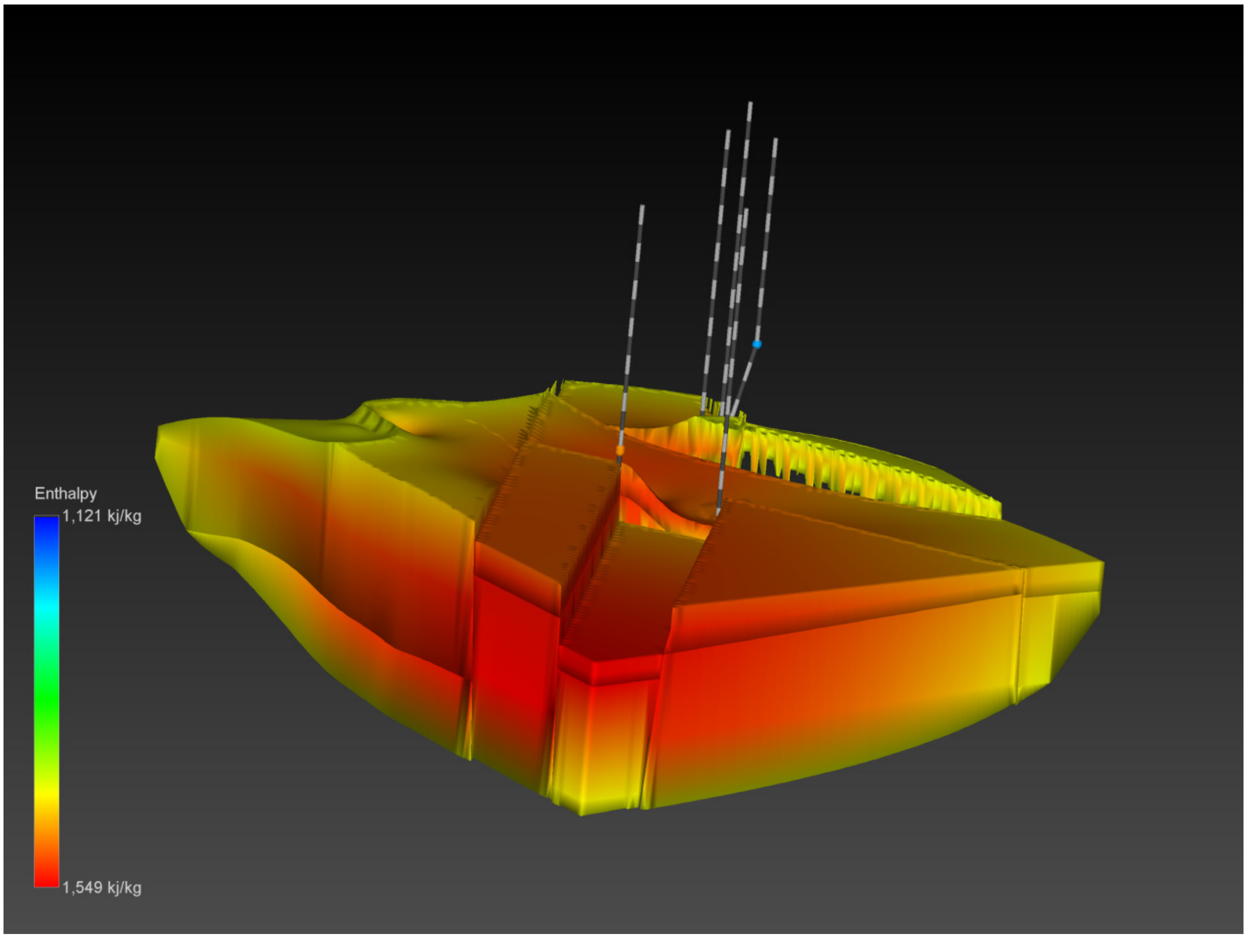

Figure 5-1. Three-Dimensional Visualization of a Subsetting Query Showing the Enthalpy Distribution About 1,400 kJ/kg.

6.0 PETRASIM TETRAD MODEL INTEGRATION

MVS can be used to support the geologic framework used as input into the prepostprocessor for the TETRAD thermal model PetraSim. To accomplish this, the faulted model must be interpolated into the PetraSim finite difference grid. The required finite difference grid was constructed in MVS by reading in a csv file or gmf containing the *x*, *y*, and *z* coordinates for the nodes of the existing PetraSim model grid using the Post Samples module and then matching the nodes with the finite difference grid builder in the Krig_3D_Geology module. The resulting grid is shown in Figure 6-1. The settings used to create the grid are shown in Figure 6-2. To implement this with the faulted Rotokawa geothermal field model, the grid parameters in Figure 6-3 need to be input into each of the seven Krig_3D_Geology modules that interpolate the separate faulted blocks as shown in Figure 3-3. The PetraSim grid has a much larger extent then the actual well data used to build the faulted block model; therefore, the trends defined in the smaller model are extended to fill the larger grid, as shown in Figure 6-4. The resulting geologic model can also be exploded along the fault planes extended through the model as shown in Figure 6-5. The coordinates and geologic data from the final model can then be exported using the Write_Coordinates module for input into PetraSim.

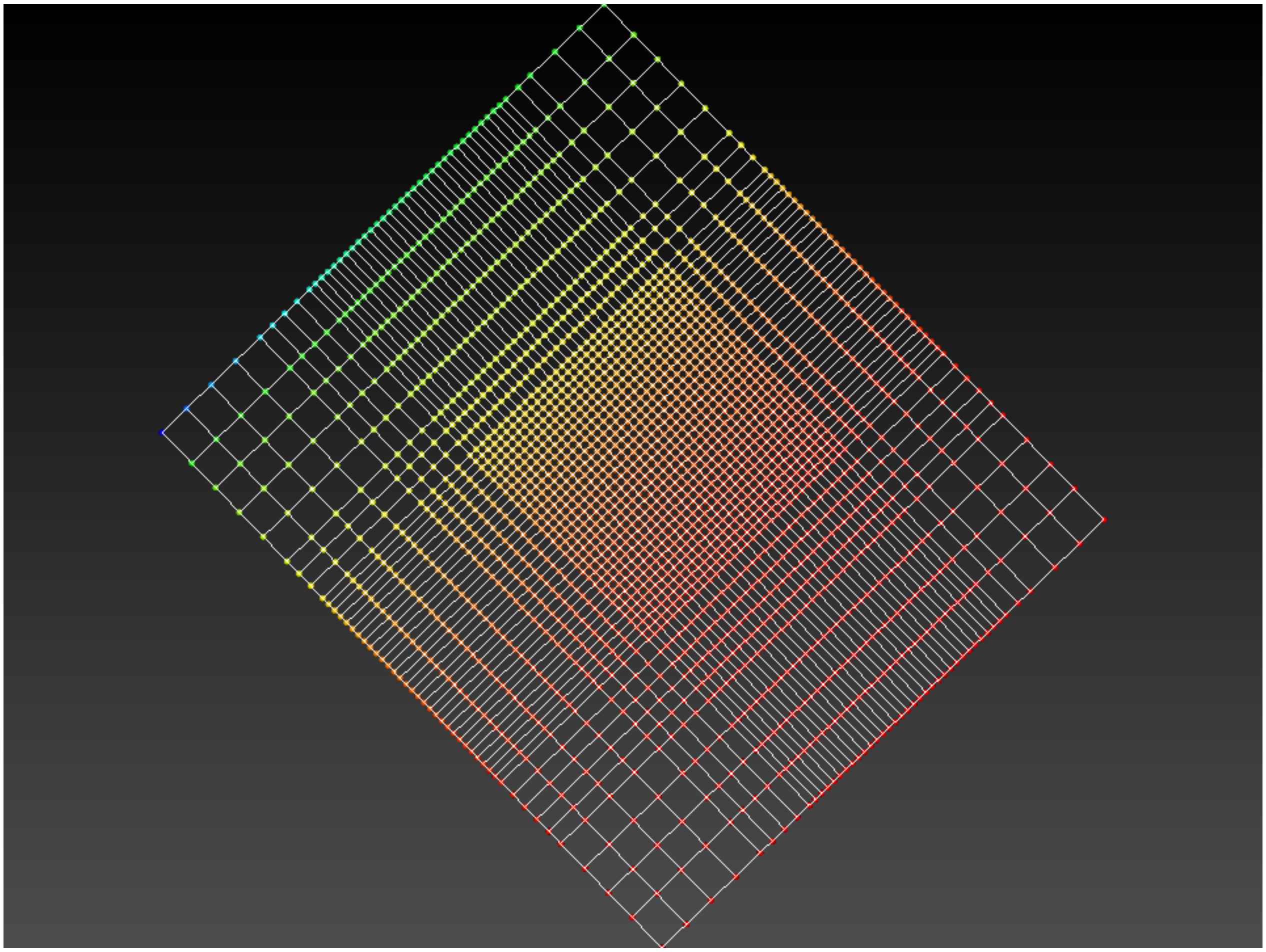

Figure 6-1. Construction of the PetraSim Grid for TETRAD Modeling in MVS for Formation Surface Interpolation.

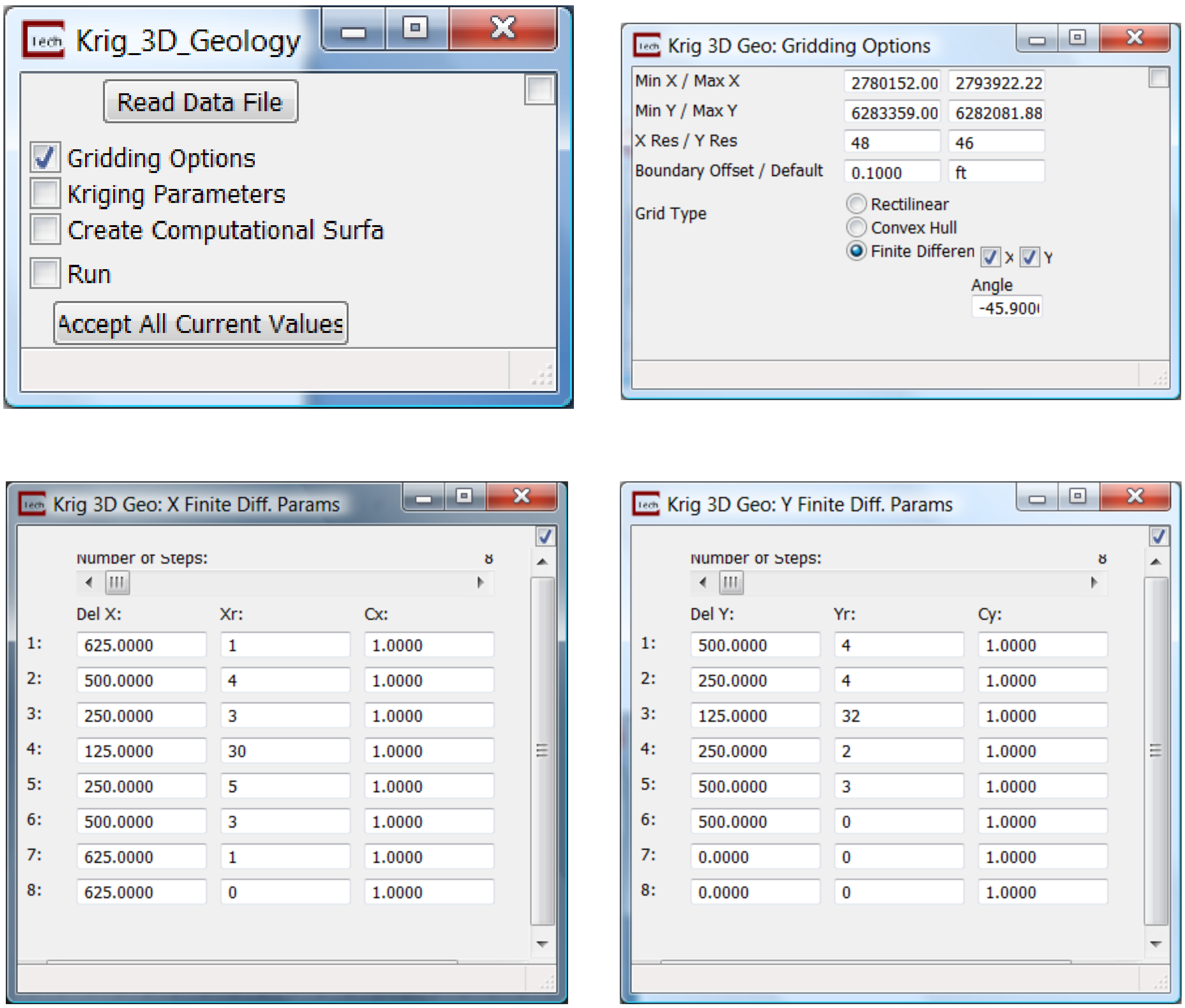

Figure 6-2. Krig_3D_Geology Module Parameter Input Windows With Parameters Used to Build the PetraSim Grid.

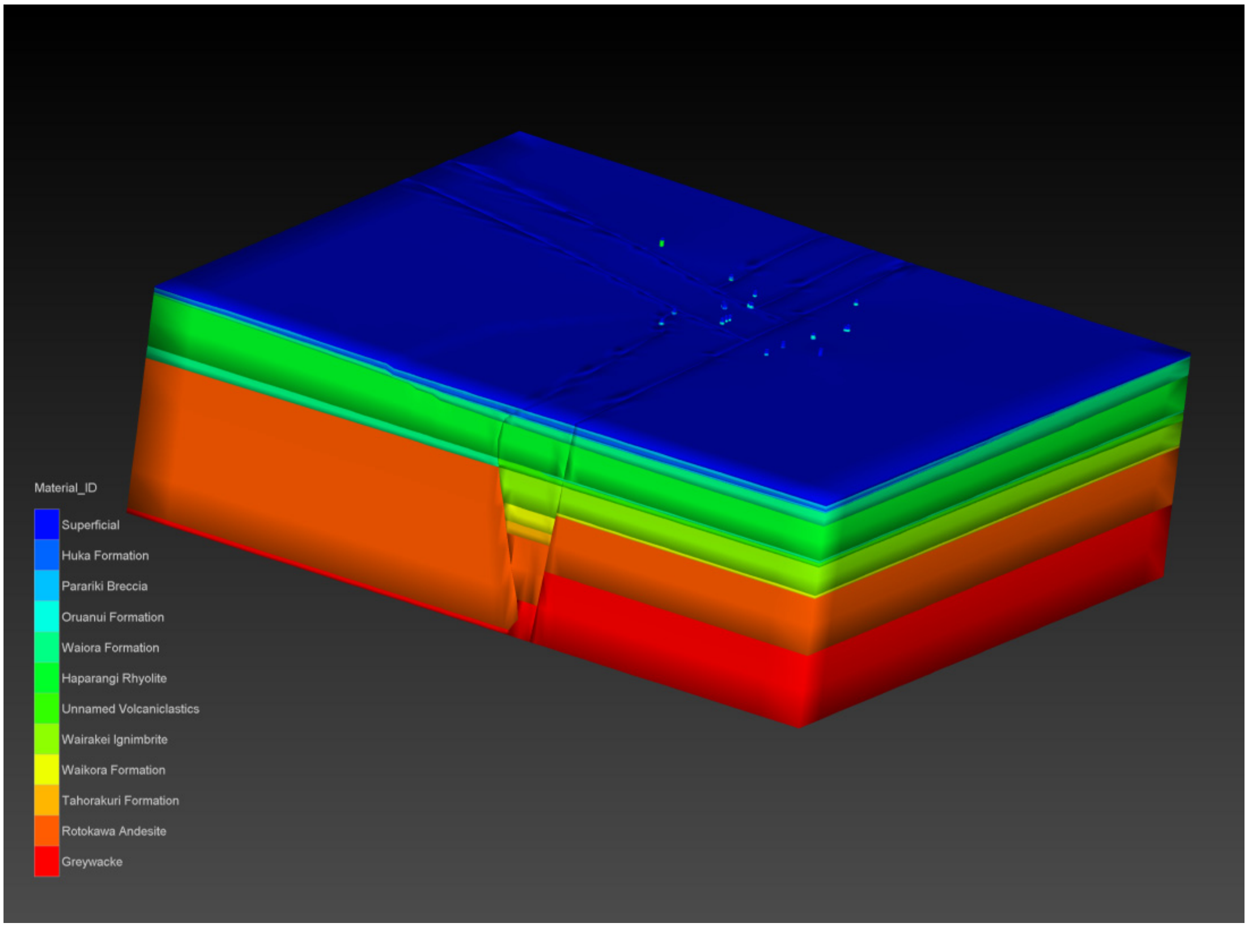

Figure 6-3. Extended Faulted Block Model Interpolated Into the PetraSim Grid.

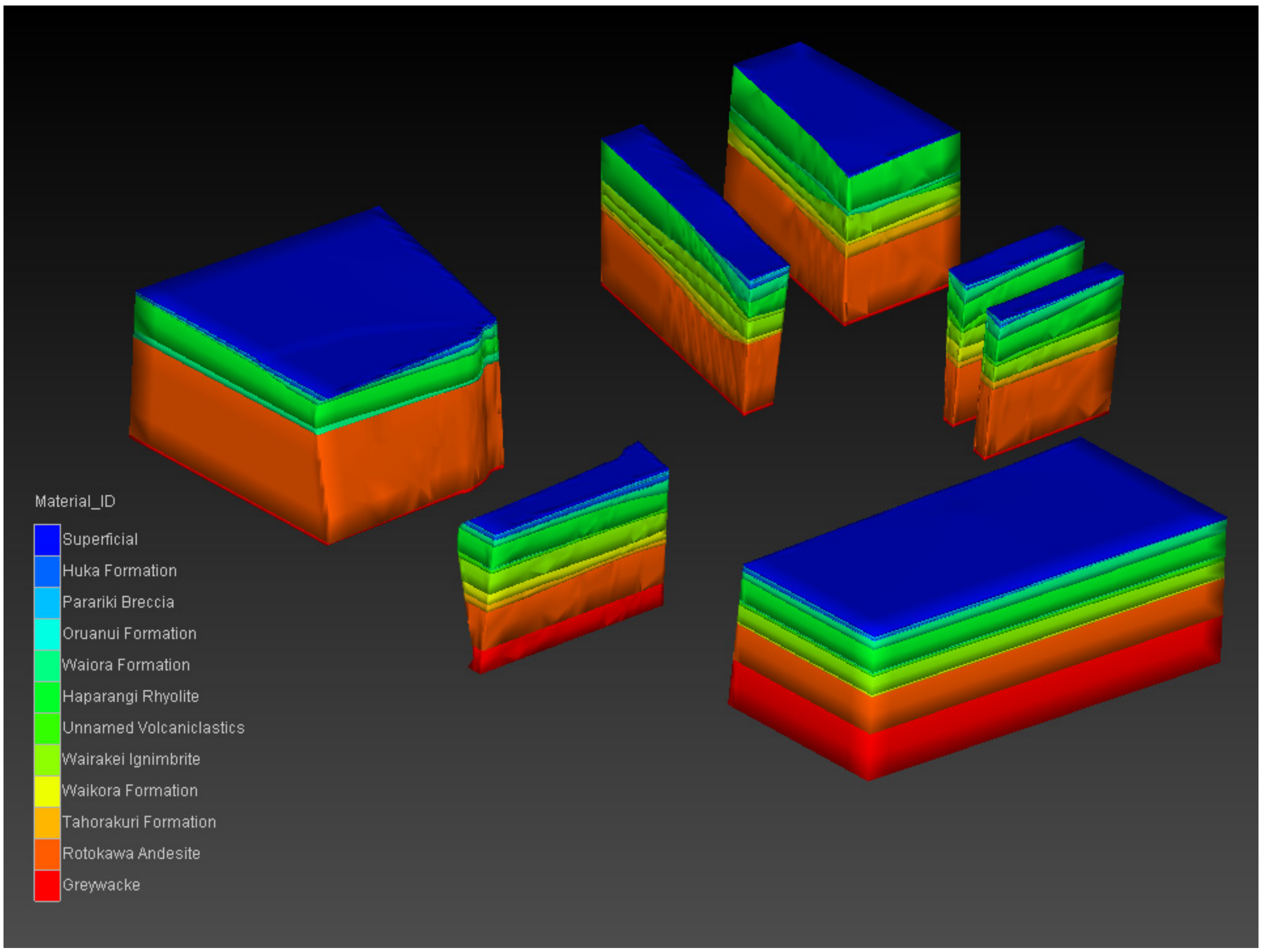

Figure 6-4. Exploded View of the Extended Faulted Block Model Interpolated Into the PetraSim Grid.

7.0 FUTURE ACTIVITES

The modeling process outlined in this report can be used to construct models and visualizations for other geothermal well fields. It is important to understand that the 3D interpolations of the data may not reflect actual values measured in further site characterization. Professional judgment must be used to evaluate whether the distribution of the interpolated values reflect probable subsurface conditions. Statistical analysis of the 3D interpolations, including confidence and uncertainty, can be displayed in 3D to help evaluate the quality of the interpolation. Even with advanced geostatisitcal algorithms and careful parameter estimation, sparse datasets can be difficult to interpolate. In the case of the Rotokawa geothermal field, enthalpy measurements are sparse, so there is a low degree of confidence and a high degree of uncertainty in the interpolation. The only way to increase the confidence of the interpolation is to add more data points to help constrain the model. The added data points may come from further measurements in the field. MVS does provide tools to identify points of the highest uncertainty to help optimize further data collection. More data points may also be generated using statistical and data mining methods outside of the MVS platform. Data mining classification algorithms can be implemented to build a supervised model to predict missing data values such as enthalpy based on multivariate associations with other data values. The predicted enthalpy values can then be added to the input file and interpolated in MVS to help increase certainty in the interpolation. Again, this does not guarantee an accurate picture of the subsurface, so professional judgment should be used to evaluate the results.