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Three-Dimensional Geologic Framework Modeling for a Karst Region in the Buffalo National River, Arkansas

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Abstract

A detailed geologic framework of surficial and subsurface geology is necessary to understand the ground water hydrologic system in karst regions. In this study, the geologic framework of a karst region adjacent to and within the Buffalo National River, Arkansas was characterized in three-dimensions. Digital geologic map data, structure contours, watershed boundaries, surface water drainage features, and digital elevation models were combined using a Geographic Information System and three-dimensional geologic modeling software to form a volumetric, three-dimensional geologic model. The resulting three-dimensional geologic model contains fourteen lithostratigraphic units, thirty-two faults, and several folds. Comparisons of the computed model to geologic cross-sections indicates that this methodology produced a model that supports the conceptual model of the subsurface. This geologic framework model is useful for visualizing geologic structures, and is an important step for understanding ground water flow, and evaluating potential contaminant transport pathways through the karst system.

INTRODUCTION

Ground water flow rates and subsurface contaminant transport rates are difficult to model and quantify in karst systems due to complex dissolution features and preferential flow. Characterization of these complex geologic features is important for understanding ground water transport processes, but generalization of geologic features are usually necessary for ground water modeling. The basic geologic features, including stratigraphic relationships (i.e. sequence, thickness, and continuity), bedding attitudes, and structural features (i.e. faulting and folding), must be spatially characterized before defining the distribution of more complex features controlling preferential flow. We use the term geologic framework modeling to refer to modeling of these basic geologic features in three-dimensions.

This paper presents the results of geologic framework modeling of a karst system in northern Arkansas, and the methodology used to integrate various types of two-dimensional geospatial data. The model area consists of six 7.5-minute quadrangles in parts of Newton, Boone, and Carroll Counties in northern Arkansas. The model area contains a large portion of the western Buffalo River watershed (fig. 1), and the Buffalo River is the dominant drainage feature here. The Buffalo River is one of the nation's few remaining undammed

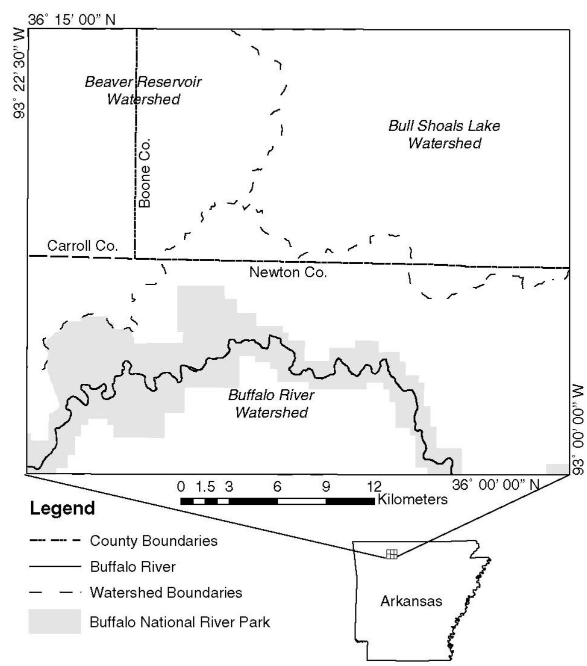

Figure 1: Location and map of the model area; showing county boundaries, the Buffalo River, watershed boundaries, and a portion of the Buffalo National River park.

rivers, and attracts over one million visitors each year for recreational activities (Mott and others, 1999).

The area surrounding the Buffalo River became a protected resource, the Buffalo National River (fig. 1), in 1972 and is managed by the National Park Service. Because baseflow and recharge water from springs constitute a large portion of the flow in the Buffalo River, characterization of ground water flow is essential for protecting the water quality in the Buffalo River hydrologic system.

DESCRIPTION OF THE MODEL AREA

The model area is located in the northeastern part of the Boston Mountains and the southern part of the Springfield Plateau in the Ozark Mountains, northern Arkansas. The model area consists of the Osage NE, Gaither, Harrison, Ponca, Jasper, and Hasty quadrangles (fig. 2) and encompasses approximately 939 square kilometers. Ground surface elevations range from 209 to 740 meters above sea level. The greatest relief is along the Buffalo River in the southern half of the model area, where the river valley is as deep as 415 meters. The climate is humid subtropical, with an average of approximately 108 centimeters of precipitation per year.

Bedrock Geology

Bedrock units largely consist of subhorizontal sequences of alternating carbonates, sandstones, and shales. Five Quaternary alluvial or colluvial units and ten geologic formations of Pennsylvanian, Mississippian, or Ordovician age are exposed at the surface and were mapped by Hudson (1998), Hudson and others (2001b), and Hudson and Murray (2002). These geologic formations were divided by Hudson and Murray (2002) into seventeen geologic map units.

Limestone and dolomite are components of six of the ten mapped geologic formations. The Mississippian Boone Formation, 104 to 129 meters thick (Hudson and others, 2001b), is exposed over 46 percent of the mapped model area and is the major host of karst features. The chert content of the Boone Formation in the model area is variable but is commonly less than 50 percent, in contrast to higher values typical elsewhere in northern Arkansas. The lower chert content may account for the continuity of karst features throughout the formation in this area.

Structurally, the model area lies in the southern flank of the Ozark Dome. The rock units are mostly gently dipping (<5 degrees) but are broken by a series of faults and monoclinal folds that formed during late Paleozoic time (Hudson, 2000a). Maximum vertical offset across individual faults, indicated by geologic mapping, ranges from 30 to 120 meters. Monoclinal folds that formed over buried faults typically have vertical relief of 20 to 40 meters and contain strata that dip 10 degrees to 25 degrees (Hudson and others, 2001a).

Surface Water Hydrology

Approximately 427 square kilometers or 46 percent of the model area are within the Buffalo River watershed. The Buffalo River originates high in the Boston Mountains, and flows into the model area near the southwestern corner, and flows eastward across the model area (fig.1). Approximately 278 square kilometers or 30 percent of the model area are part of the Bull Shoals Lake watershed. Approximately 230 square kilometers or 25 percent of the model area are part of the Beaver Reservoir watershed. These watersheds are sub basins of the Upper White River that flows to the southeast as a tributary of the Mississippi River.

Karst Features and Ground Water Hydrology

In many geologic settings the area of recharge for a ground water system is contained within the topographic divides that form the watershed boundaries. However, in karst systems ground water flow in the subsurface often crosses the surface watershed boundaries. Knowledge about this component of interbasin flow is important for understanding the interactions of the ground water and surface water hydrologic system, and for evaluating potential contaminant transport pathways through the karst system.

The stratigraphic distribution of karst in the model area can be inferred from an inventory of caves located within the boundaries of western Buffalo National River, although this inventory may exclude caves in upper formations that lie within the watershed but outside the park corridor. Of 96 inventoried caves, 78 percent are within limestone of the Boone Formation, 17 percent are in limestone or dolomite intervals within the Everton Formation, and the remaining are in limestone of the lower part of the Bloyd Formation (Hudson and others, 2001a). Caves within the Boone Formation are distributed throughout its thickness, but entrances are slightly more common within 12 m of the upper or lower contact. The upper Boone contact is overlain by the 2- to 12-m-thick Batesville Sandstone that is commonly slumped into solution cavities within Boone limestone. The basal Boone limestone unconformably overlies sandstone of the Everton Formation, and the contact is marked by the greatest number of springs within the western Buffalo River watershed. This relation illustrates that the Boone Formation is the main karst aquifer for the region and that the Everton Formation behaves as a confining unit.

Dye-tracer studies documented that some large springs gather recharge from far beyond the surface watershed boundaries (Mott and others, 1999). Erosion of the Buffalo River valley left most karst aquifers perched above the current river level and, consequently, their local base-level elevations are controlled by relief across structures. Down-dropped blocks of Boone Formation host both the largest springs and the most extensive cave systems known within the model area.

Field observations and dye-tracer studies by Mott and others (1999) indicated that water discharged from some springs in the Buffalo River watershed originated in the Bull Shoals Lake watershed. Mott and others (1999) used these data to compute ground water velocities exceeding 640 meters per day. Because much of the Bull Shoals Lake watershed in the model area is covered by agricultural land, consisting mostly of livestock operations, it is possible that nutrient contaminants from these agricultural activities will reach the Buffalo River by interbasin transfer of water.

DATA COMPILATION

During geologic mapping, locations and elevations of geologic features were recorded using a topographic base map, Global Positioning System (GPS), and altimeter. Geologic features drawn in the field, GPS data points, and aerial photograph information were compiled to form the geologic maps by Hudson (1998), Hudson and others (2001b), and Hudson and Murray (2002). These geologic map data were digitized and attributed in a Geographic Information System (GIS) database. Additional unpublished geologic map data by Hudson (2000b), Lucas (1971), and McMoran (1968) were digitized in GIS and used to supplement more complete geologic map data. A comprehensive GIS database of these geologic map data, extent shown in fig. 2, was developed by the authors for use in geologic framework modeling.

Geologic map units, and major surface water bodies were represented as polygon features. Lithologic contacts, faults, folds, structure contours for the base of the Boone Formation, and minor surface water drainage features were represented as line features. Bedding attitudes and other geologic structure information were represented as point features. Digital elevation model (DEM) data, 10-meter spatial resolution from the U.S. Geological Survey, were used to recreate surface topographic relief and define the watershed boundaries within the model area. Supplemental GIS data (i.e. county boundaries, minor surface water drainage features, and land-use information), used as reference information, were obtained from various on-line data repositories.

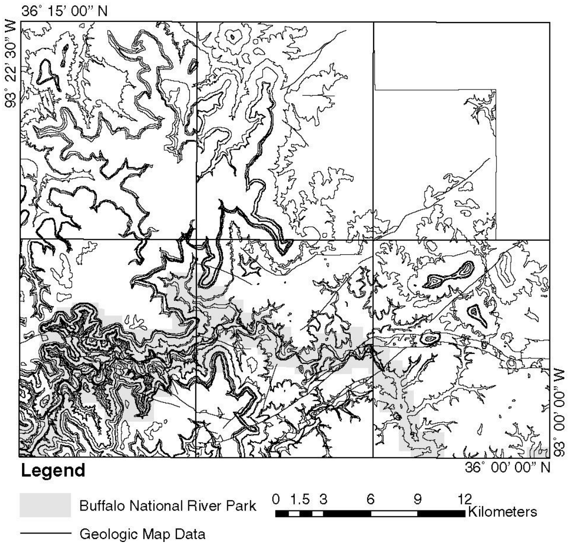

Figure 2: Map showing the extent of published and unpublished geologic map data and quadrangle boundaries.

GEOLOGIC MODELING PROCEDURE

The three-dimensional modeling software requires input of longitude (x), latitude (y), and elevation (z) coordinates of data points on geologic surfaces (lithostratigraphic contacts, faults). These data were obtained during geologic mapping, but took three forms of different quality. The highest quality data were field sites on contacts or faults that were located during mapping via one or a combination of a GPS receiver, altimeter, or distinctive topographic location. These field sites formed the basis from which other data forms were constructed. Secondary data sources were the traces of geologic planes over surface topography. During construction of the geologic maps, these map traces were anchored to the field sites but were often interpolated between sites on the basis of distinctive topographic features (e.g., ledges) that provided further qualitative control on the spatial variation of the planes. Finally, for the Boone Formation, structure contours were interpreted from the control sites on its upper and lower contacts, the formation thickness, measured attitudes of beds and faults and lacking other constraints, geologic interpretations of the structural configuration of the area.

Pre-Processing of Geologic Model Input Data

Geologic map data were digitized and attributed in GIS format for ninety-three percent of the model area (fig. 2). These data were most easily transferred from the GIS database to the geologic modeling software in American Standard Code for Information Interchange (ASCII) format. Points of contact between lithostratigraphic units were exported from the GIS with x and y coordinates. Separate ASCII files were maintained for the top of each lithostratigraphic unit. The z coordinates of these points of contact were calculated from the 10-meter spatial resolution DEM and added to the ASCII files.

Supplementary lithostratigraphic points of contact were derived from structure contours of the elevation of the base of the Boone Formation. Lithostratigraphic points of contact were exported from the GIS with x, y, and z coordinates. These data points were used in addition to the geologic map data to define the top of the Everton Formation in the geologic framework model.

Major mapped faults were also included in the geologic framework model. The surface traces of the major mapped faults were exported as a series of points from the GIS with x and y coordinates. Separate ASCII files were maintained for each major fault. The elevations of these points were calculated from intersections with the 10-meter spatial resolution DEM and added to the ASCII files. The average dip direction (in azimuthal units) and inclination of the faults were added to the respective ASCII fault files. From these data, additional points were calculated in three-dimensional space to represent the shape of the fault surface.

Geologic Units and Structures

Surface topography, fourteen lithostratigraphic units, and thirty-two faults were modeled in three dimensions. The surface topography was modeled as an unconformity at the top of the stratigraphic sequence using DEM data as a continuous surface. The tops of the following lithostratigraphic units, listed in increasing geologic age, were modeled: Atoka Formation, Upper Bloyd Formation, Lower Bloyd Formation, Prairie Grove Member of the Hale Formation, Cane Hill Member of the Hale Formation , Pitkin Limestone, Wedington Sandstone Member of the Fayetteville Shale, main body of the Fayetteville Shale, Batesville Sandstone, main body of the Boone Formation, St. Joe Limestone Member of the Boone Formation, Everton Formation, Powell Dolomite, and the Cotter Formation.

The relative amount of data used as input for these formations is summarized in Table 1 by showing the length of the upper contact mapped in the model area. The lengths of the mapped contacts for the Boone and Everton Formations were greatest in the model area, thus these geologic formations were well controlled in the geologic framework model. The upper contacts (surfaces) of the lithostratigraphic units were computed by interpolating between data points along the geologic map contacts and extrapolating to the model boundaries using the two-dimensional minimum-tension gridding algorithm (Dynamic Graphics Incorporated, 1998). The thicknesses of these lithostratigraphic units were then calculated as the differences between adjacent surfaces.

Lithostratigraphic units with fewer input data (Atoka, Powell, and Cotter) were modeled using data points that represented the top of the lithostratigraphic units, and by maintaining thicknesses relative to reference lithostratigraphic units (units with higher relative amounts of input data). The Atoka Formation referenced the Upper Bloyd Formation, the Powell Dolomite referenced the Everton Formation, and the Cotter Formation referenced the Everton Formation. Quaternary units and the Ordovician Fernvale Limestone were not modeled because of their thinness and lack of spatial continuity.

Thirty-two major faults were incorporated into the geologic framework model. The fault inclinations ranged from forty degrees to eighty-five degrees from horizontal with an average

Table 1: Summary of modeled lithostratigraphic units

Mapped Unit Name	Length of Mapped Upper Contact (meters)
Atoka	150m-constant thickness
Upper Bloyd	39,985
Lower Bloyd	283,799
Prairie Grove	255,975
Cane Hill	158,955
Pitkin	59,520
Wedington	40,053
Fayetteville	59,555
Batesville	291,551
Boone	453,939
St. Joe	315,198
Everton	382,109
Powell	10,720
Cotter	1,204

fault inclination of seventy-four degrees. Twenty-seven of the thirty-two faults were inclined at angles greater than or equal to seventy degrees.

EVALUATION OF GEOLOGIC FRAMEWORK MODEL RESULTS

The quality of the geologic framework model may be evaluated by comparing cross-sectional views generated from the model to cross-sections published with the geologic mapping. Cross-sectional views through the Jasper quadrangle (Hudson and others, 2001b) were used for these comparisons. The cross-section A-A' (Hudson and others, 2001b) is shown as Figure 3a; and the corresponding cross-sectional view computed from the geologic framework model is shown as Figure 3b. The cross-section B-B' (Hudson and others, 2001b) is shown as Figure 4a; and the corresponding cross-sectional view computed from the geologic framework model is shown as Figure 4b.

The geologic framework model includes two formations that were not recognized during geologic mapping in the Jasper quadrangle. These formations, the Atoka Formation (youngest Pennsylvanian unit) and the Cotter Formation (oldest Ordovician unit), were identified during mapping of the Ponca

Figure 3a: Cross Section A-A' from Hudson and others (2001b).

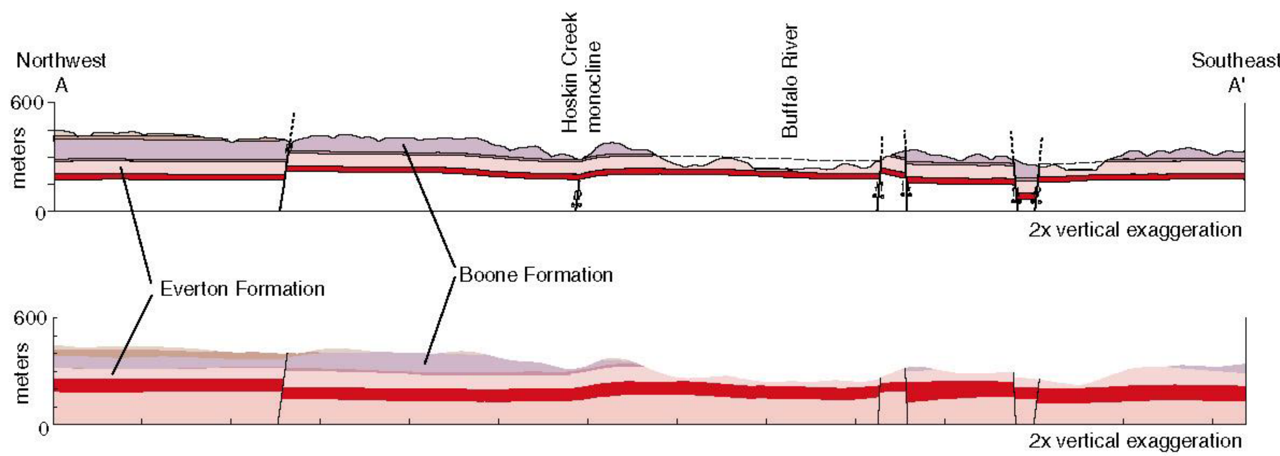

Figure 3b: Cross Section A-A' computed from the Geologic Framework Model.

Figure 4a: Cross Section B-B' from Hudson and others (2001b).

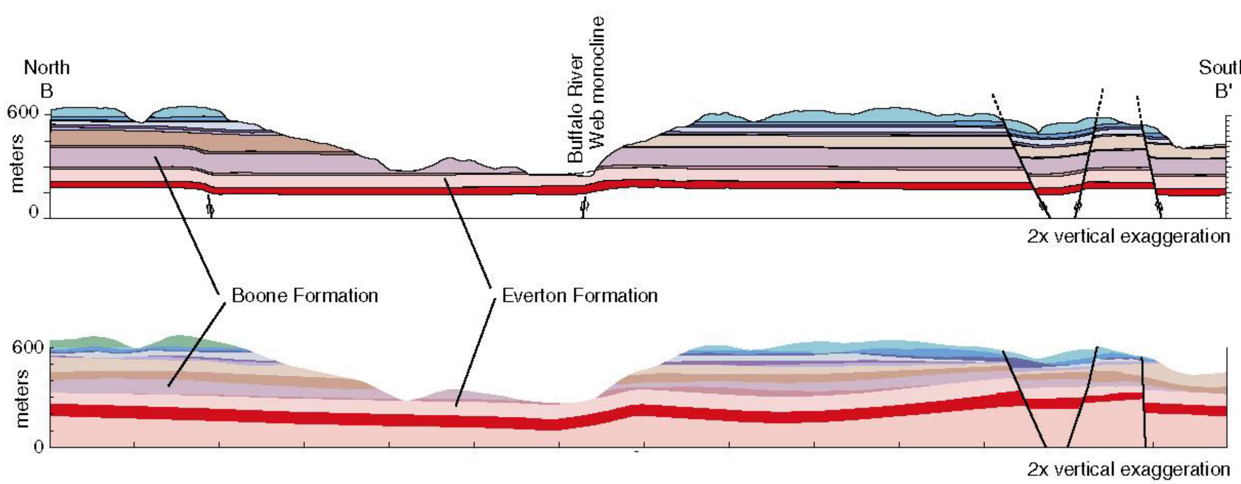

Figure 4b: Cross Section B-B' computed from the Geologic Framework Model.

quadrangle by Hudson and Murray (2002), and added to the geologic framework model.

Visual inspection of these cross-sections indicates that the thicknesses of the Boone Formation, and the Everton Formation are similar between the published cross-sections and the geologic framework model. Slight variations in lithostratigraphic unit thicknesses occur near A', the southeastern portion of the Jasper quadrangle, and are probably due to a sparse distribution of points of lithostratigraphic contact in this area. Thicknesses of the thinner lithostratigraphic units are not as well maintained in the geologic framework model, but may be less important for understanding this karst system. Structural features and offset of lithostratigraphic units along the fault surfaces are captured very well by the geologic framework model. Offset direction along 4 out of 5 faults in A-A', and 2 out of 3 faults in B-B' are correctly built by the geologic framework model. The Hoskin Creek monocline, in A-A', and the Web monocline, in B-B' are correctly captured by the geologic framework model.

In the model area, the Boone Formation is the most significant karst aquifer unit. Accurately modeling the distribution of this geologic unit is an important step for understanding ground water flow in the model area. The distribution of the Boone Formation (main body and St. Joe Limestone Member), computed in geologic framework modeling, is shown as Figure 5. The resulting geologic framework model indicates that the Boone Formation is continuous throughout most of the model area, with the exception of the Buffalo River valley where the main body of the Boone was eroded away.

CONCLUSIONS

The methodology described in this paper was effective for constructing a three-dimensional digital geologic framework model in northern Arkansas. These procedures may be useful in other areas where there are substantial topographic relief, surface exposures of several relatively flat-lying lithostratigraphic units, and normal or strike-slip faults. Successful development of the geologic framework model in this study relied on high quality geologic map data. Fault dip directions and fault inclinations were required to accurately capture structural geologic features. Use of this procedure required careful digitization and attribution of geologic map data in a GIS format.

The geologic framework model indicates that extensive surface exposures of the Boone Formation are located in the northeastern part of the model area where agriculture is the dominant land-use. The model also indicates that the channel of the Buffalo River is below the main body of the Boone Formation along its entire length, therefore springs from the base of the Boone could directly recharge the Buffalo River. The areas where the Boone is exposed should be the focus of studies to characterize the distribution of dissolution features, and dye-tracer studies to define pathways of travel between dissolution features and springs recharging the Buffalo River.

Additional lithologic data or property data (e.g. distribution of permeability) acquired during the installation of ground water wells would be valuable additions to this model. Borehole geophysical logs or surface geophysics could also contribute control points for lithostratigraphic contacts in the subsurface. These data would be useful for refining the modeling methodology and adding control points to computations in the subsurface.

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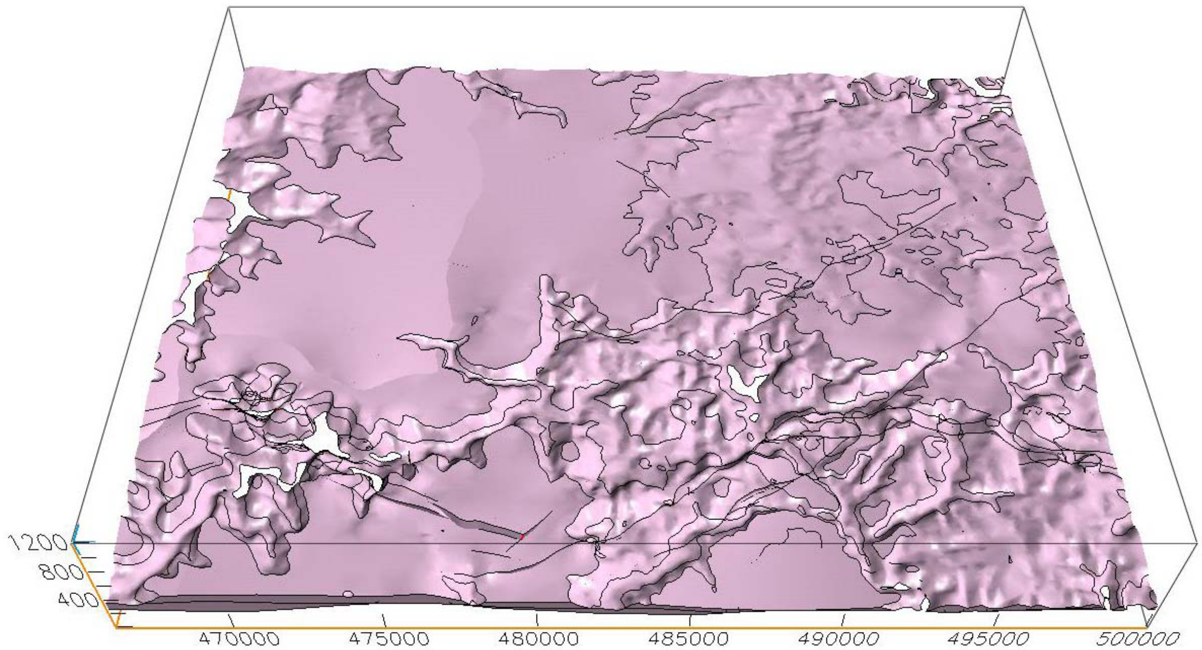

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