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Evolution of 3-D Geologic Framework Modeling and Its Application to Groundwater Flow Studies

In this Fact Sheet, the authors discuss the evolution of project 3-D subsurface framework modeling, research in hydrostratigraphy and airborne geophysics, and methodologies used to link geologic and groundwater flow models.

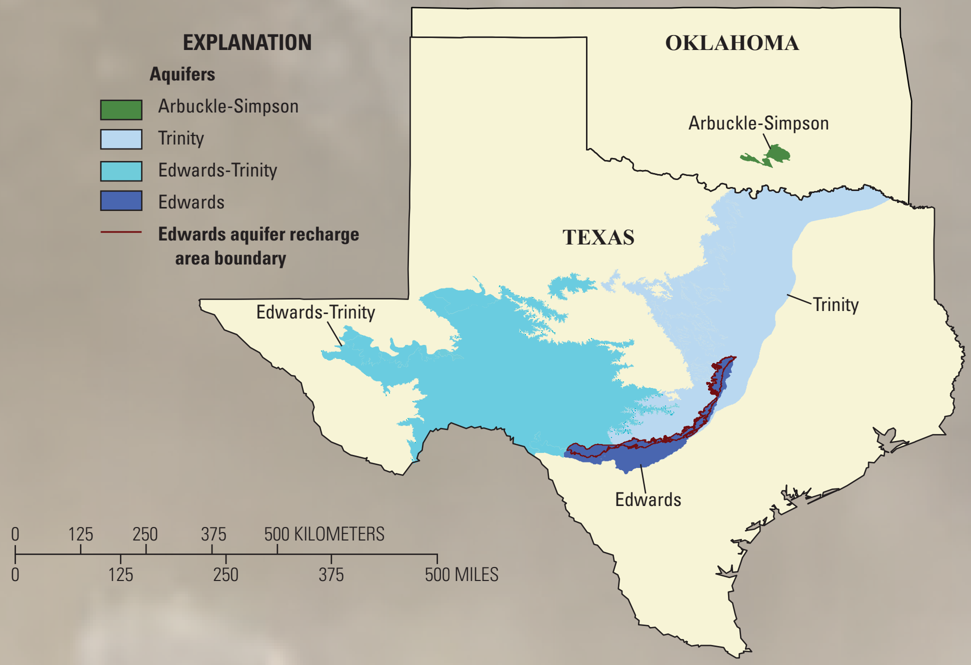

Figure 1. Location map of the Arbuckle-Simpson and Trinity aquifers and Edwards aquifer recharge area.

The various geologic processes that shape the Earth's surface and subsurface all operate in three-dimensional (3-D) space. Within the U.S. Geological Survey (USGS), the greatest needs and applications for 3-D modeling include the following: (1) visualization of surface geology into the subsurface, (2) interpretation and verification of the geology and its controlling fault structures, and (3) application of 3-D model data for investigating geologic issues (Jacobsen and others, 2011).

Three-dimensional geologic modeling of an aquifer can quantitatively depict the connectedness of rock units across fault and fracture zones. This modeling allows geologists to determine the distribution of geologic units, structural features, and other controlling factors, such as ***porosity*** and ***permeability***. These parameters are complex variables that reflect original depositional conditions, alteration, dissolution, and dislocation. Geologic 3-D framework modeling also is useful for visualizing the interactions of fault and related structural features.

Three-dimensional geologic framework models can be directly converted into groundwater flow models, such as ***MODFLOW***. Construction of the 3-D geologic architecture of an aquifer needs to be the first step in using geologic properties to constrain groundwater flow models. This first-step approach takes much of the subjective guesswork out of constructing model layers and results in a model that is more realistic and representative of the actual subsurface hydrologic conditions of the groundwater basin being modeled.

Several USGS projects, supported by the National Cooperative Geologic Mapping Program (NCGMP), are using multidisciplinary approaches to reveal the surface and subsurface geologic framework of three important groundwater aquifers: the Edwards, Trinity, and Arbuckle-Simpson (fig. 1). In this Fact Sheet, the authors discuss the evolution of project 3-D subsurface framework modeling, research in hydrostratigraphy and airborne geophysics, and methodologies used to link geologic and groundwater flow models. The principal sections of this Fact Sheet are as follows:

porosity	**Ratio of the volume of voids in a material to the total volume of the porous medium**
permeability	**Rate of flow of a fluid through a porous material**
MODFLOW	**Freely available USGS computer software to simulate the flow of groundwater through aquifers**

1 **Geologic Framework of the Edwards and Trinity Aquifers**

2 **Geologic Framework of the Arbuckle-Simpson Aquifer**

3 **Arbuckle-Simpson 3-D Geologic Framework Model to Groundwater Flow Model**

4 **Arbuckle-Simpson MODFLOW Model**

1 Geologic Framework of the Edwards and Trinity Aquifers

The Edwards aquifer in Texas is one of the most productive freshwater aquifers in the world. It has been designated a sole source aquifer by the U.S. Environmental Protection Agency (EPA) and is the primary source of water for San Antonio, the Nation's seventh largest city. Understanding the Edwards is essential for maintaining habitat for several threatened and endangered species. The Trinity aquifer forms the catchment area for the Edwards aquifer, and it intercepts some surface flow above the Edwards recharge area. The Trinity aquifer also may contribute to the Edwards' water budget by subsurface flow across formation boundaries at considerable depths. Dissolution, karst development, and faulting and fracturing in both of these carbonate-rich aquifers directly control aquifer geometry by compartmentalizing the aquifer and creating unique groundwater flow paths.

Three-dimensional modeling studies of aquifer-bearing units in south-central Texas concentrated on the area's carbonate-rich ***hydrostratigraphic units***, and underscored the importance of airborne ***electromagnetic*** data for defining new unit contacts and fault structures (Blome and others, 2006). Two 3-D models discussed as follows highlight key controls on aquifer permeability and provide insights on subsurface aquifer processes and aquifer boundaries and interfaces. The proprietary software EarthVision (EV) was used because of its ability to combine various data types and accurately define faulted surfaces while maintaining stratigraphic and structural integrity and complexity.

The 3-D EV model of northern Bexar County (fig. 2) reveals the subsurface geology and groundwater flow units of the Edwards and Trinity aquifers, where water wells range from 60 to over 300 meters in depth. This 3-D model is based on mapped geologic relations that reflect: (1) Balcones fault zone structures, (2) detailed interpretations of 40 principal wells, and (3) gross geometry of the Edwards Group hydrostratigraphic units derived from prior interpretations of depositional environments and paleogeography. The 3-D model was also constructed to determine whether hydrostratigraphic units could be accurately modeled in the subsurface and to visualize the lateral connections between hydrostratigraphic units of contrasting permeability across fault strands.

A 3-D EV model of the rock units of the Edwards and Trinity Groups in the north Seco Creek area of Medina and Uvalde Counties, Texas (fig. 3), was constructed using a variety of digital datasets, such as: (1) geologic maps, including the current geologic map of the area (Blome and others, 2004); (2) lithologic descriptions, interpretations, and geophysical logs from 31 drill holes; (3) helicopter electromagnetic geophysical data (Smith and others, 2003); and (4) known major and minor faults in the study area. This model reveals the complex intersections of both major and minor faults in the subsurface, and the impact these faults have on the continuity of the Trinity and Edwards aquifer-forming units.

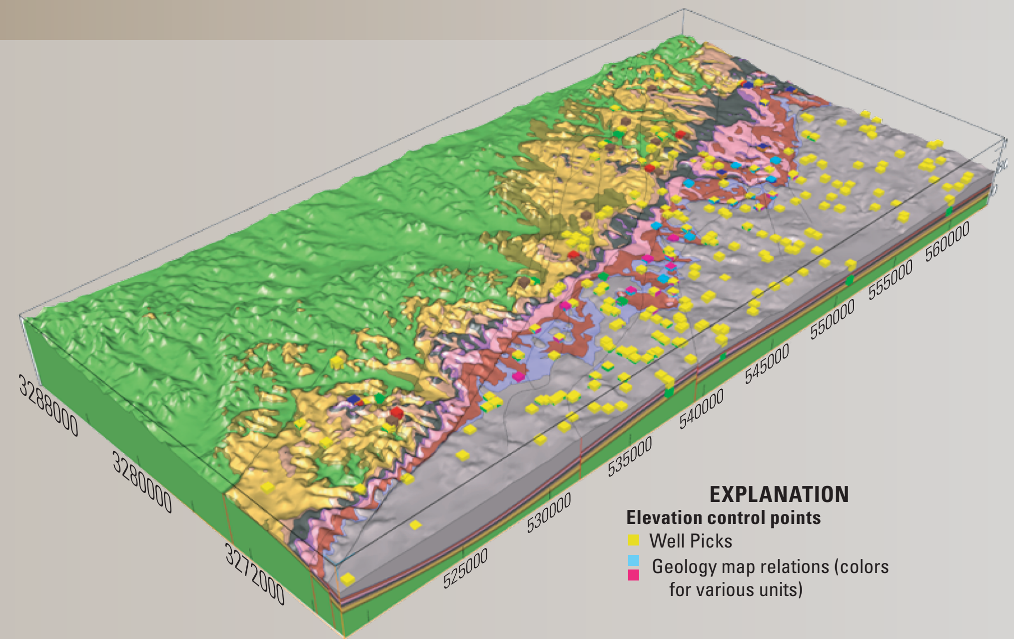

Figure 2. Three-dimensional model of northern Bexar County, Texas (Pantea and Cole, 2004).

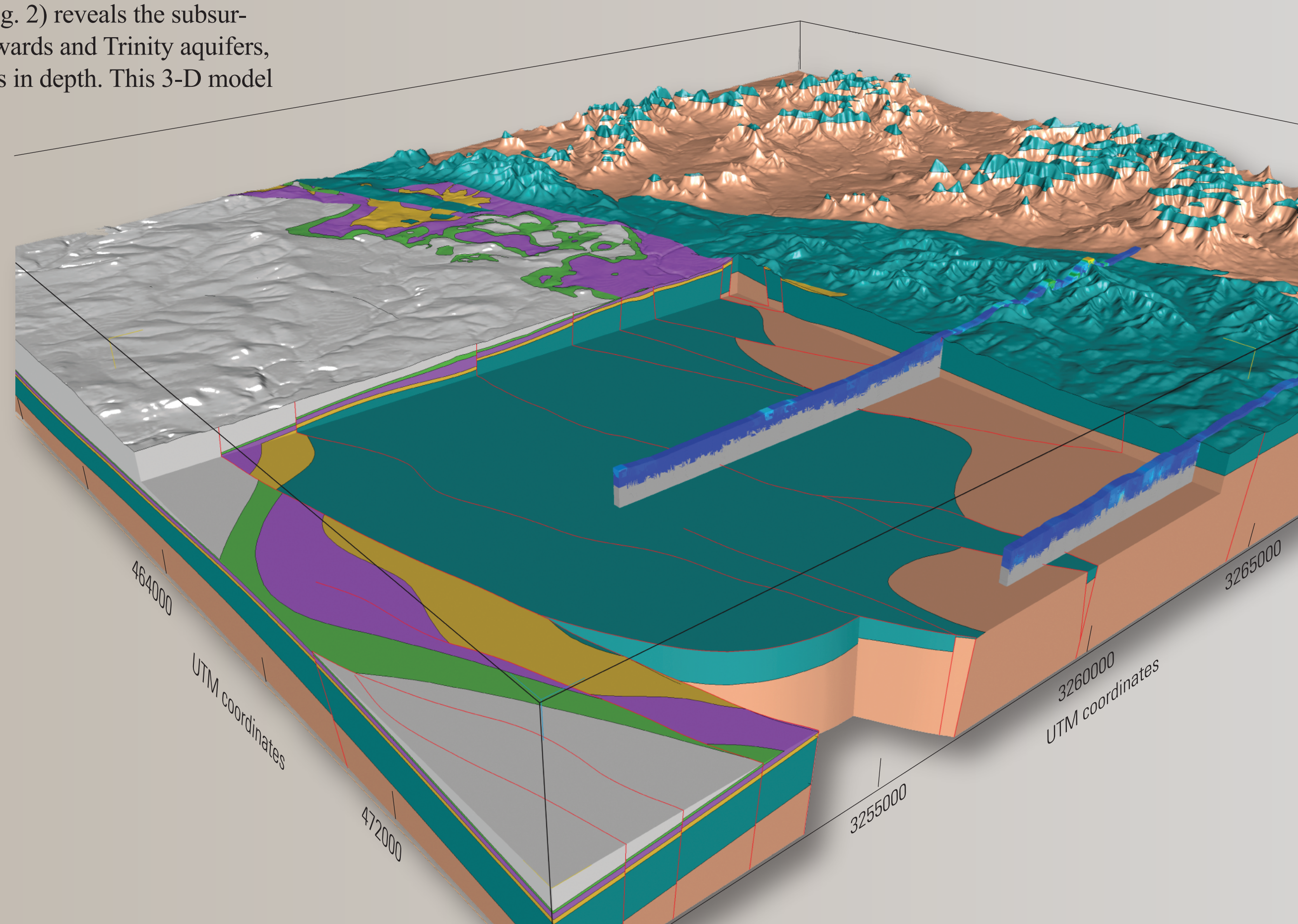

Figure 3. Three-dimensional model of the north Seco Creek area of Medina and Uvalde Counties, Texas (Pantea and others, 2008). Multiple fault structures (shown in red) and electromagnetic geophysical profiles (shown as blue and gray fences) were used to construct the model.

hydrostratigraphic unit	**Body of rock that forms a distinct hydrologic unit with the flow of groundwater**
electromagnetic	**Ability to emit or transfer energy in the form of electromagnetic waves**

2 Geologic Framework of the Arbuckle-Simpson Aquifer

The Arbuckle-Simpson aquifer of south-central Oklahoma (fig. 1) encompasses more than 850 square kilometers and provides water for public drinking supply, farming, mining, conservation, and recreation. The aquifer also contains a number of unique freshwater and mineral springs, such as Buffalo spring (fig. 4), in the Chickasaw National Recreation Area.

The aquifer's eastern groundwater basin (Hunton anticline area, fig. 5) has been designated a sole source aquifer by the EPA. Proposed development of water supplies from the aquifer led to concerns that large-scale withdrawals of water would cause decreased flow in rivers and springs, which in turn could result in the loss of surface water supplies, recreational opportunities, and aquatic habitat.

The Oklahoma Water Resources Board, in collaboration with the Bureau of Reclamation, the USGS, Oklahoma State University, and the University of Oklahoma studied the aquifer to determine the volume of water that could be withdrawn while protecting springs and streams. The USGS NCGMP, in cooperation with the USGS Oklahoma Water Science Center and other Federal and State agencies, supported construction of a 3-D EV framework model of the water-producing Hunton anticline area. Construction of the model was challenging due to the folded, faulted, and fractured nature of the Hunton anticline geology (fig. 5), variable unit thicknesses (from 600 to 2,750 meters), and scarcity of well information.

Figure 4. Buffalo spring, Chickasaw National Recreation Area, south-central Oklahoma.

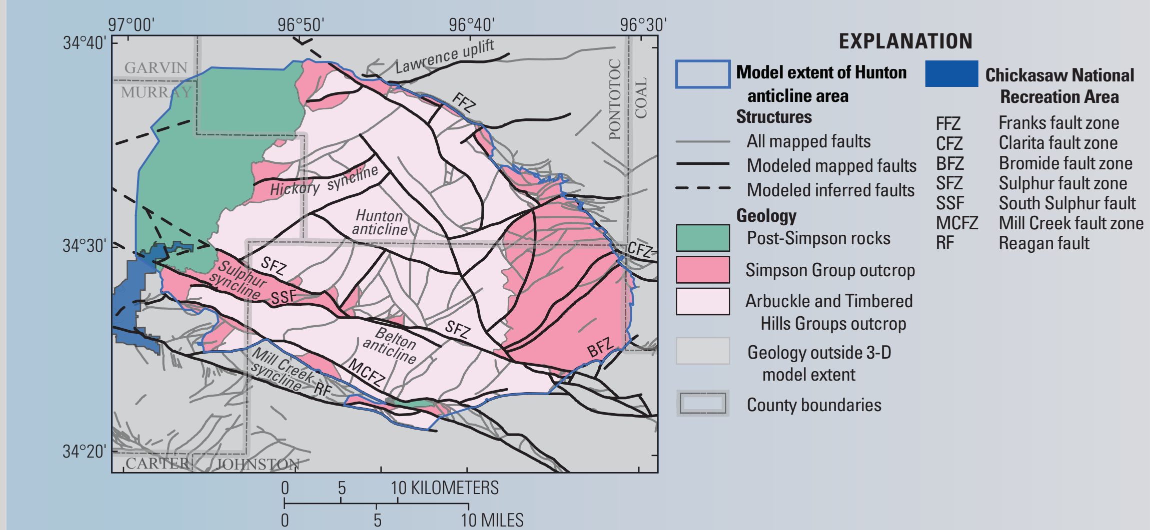

Figure 5. Geology of the Arbuckle-Simpson aquifer's Hunton anticline area, south-central Oklahoma (outlined in blue), and its major and minor fault structures (Faith and others, 2010).

This 3-D framework model was constructed to quantify the geometric relations of four hydrostratigraphic units of the Arbuckle-Simpson aquifer in the Hunton anticline area (Faith and others, 2010). The model (fig. 6) shows the volumetric extents of the Arbuckle and Timbered Hills Groups (light pink) and Simpson Group (dark pink) rocks, which are the primary water-bearing units of the aquifer. The data used to define the model and modeled surfaces were obtained from geophysical logs, cores, and cuttings from 126 water and petroleum wells.

The model stratigraphic contacts and faults were defined from the surface geologic mapping by Johnson (1990) and the geospatial map database of Cederstrand (1996). The top of the basement was defined using data from 13 drill holes. The top of the Arbuckle-Timbered Hills Group was picked from 89 drill holes and represents the model's primary reference surface, which was used to define other model surfaces. The top of the Simpson Group was identified in 54 wells. Locally, pre-erosional surfaces for the Simpson Group and basement model units were projected based on the x-, y-, and z-values of a known contact. The post-Simpson model unit was defined as the volume between the top of the Simpson Group and the surface of the digital elevation model. Over much of the model area, post-Simpson rocks are missing because of erosion.

Geophysical data, including a helicopter electromagnetic survey (Smith and others, 2011), were used as follows: (1) to precisely locate mapped faults, (2) to identify shallow faults that have no recognizable surface expression, (3) to refine the outcrops of the lithostratigraphic units, and (4) to map the transition between freshwater springs in the east and saline springs in the west. A map of apparent resistivity over one survey block on the southwestern flank of the Hunton anticline (fig. 7) represents rock units with clarity and detail unachievable by using traditional field geology mapping techniques.

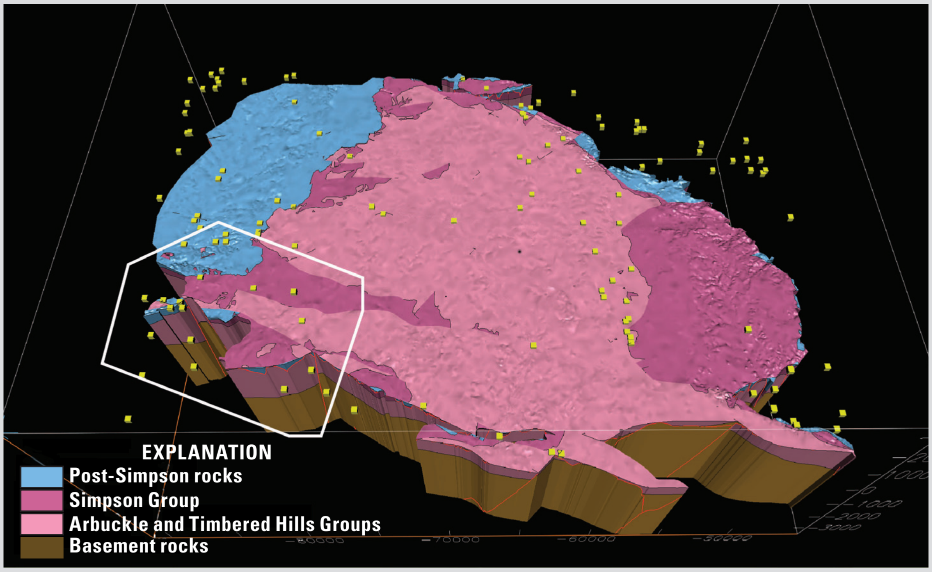

Figure 6. A perspective view of the 3-D geologic framework model of the Arbuckle-Simpson aquifer (Faith and others, 2010). The yellow boxes represent the wells used to construct the model. The white polygon outlines the area of the helicopter electromagnetic survey shown in figure 7.

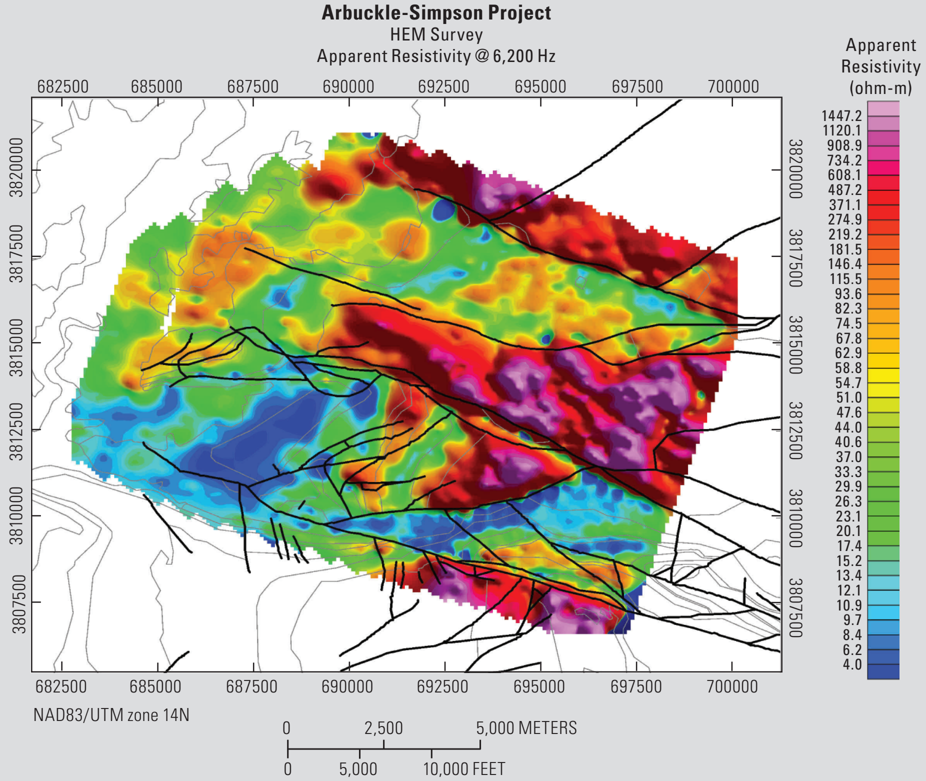

Figure 7. Apparent resistivity map from the helicopter electromagnetic survey on the southwestern flank of the Hunton anticline (Smith and others, 2011). Previously mapped geologic contacts and faults are shown as gray and black lines, respectively.

3 Arbuckle-Simpson 3-D Geologic Framework Model to Groundwater Flow Model

The boundary of the 3-D EV model of the eastern Arbuckle-Simpson aquifer (fig. 6) precisely matches the MODFLOW model developed by the USGS as part of the Arbuckle-Simpson Hydrology Study, which was led by the Oklahoma Water Resources Board and the USGS Oklahoma Water Science Center. Hydrostratigraphic surfaces in EarthVision were sampled and interpolated to match nodes in the MODFLOW model. These nodes provide the land-surface elevations and the thicknesses of the Arbuckle and Timbered Hills Groups, Simpson Group, and the post-Simpson units across the entire MODFLOW model domain. The Arbuckle and Timbered Hills Groups make up the major part of the aquifer for thickness, outcrop extent, and volume of groundwater (fig. 8).

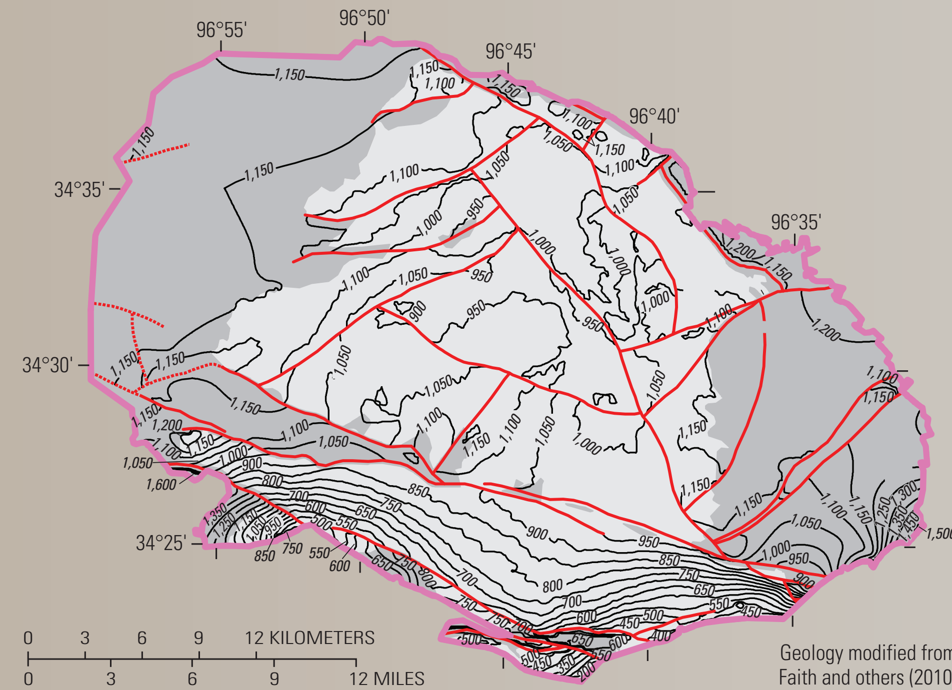

Figure 8. Thickness of the Arbuckle and Timbered Hills Groups, and faults modeled by the 3-D EarthVision geologic framework model (Christenson and others, 2011).

4 Arbuckle-Simpson MODFLOW Model

A MODFLOW groundwater-flow model was specifically developed to simulate discharge to streams and springs in the eastern Arbuckle-Simpson aquifer (Christenson and others, 2011). Six layers of 200-meter cells were used to represent the aquifer over a total area of 1,002 square kilometers. The resulting simulated potentiometric map (fig. 9) represents over 25,000 data points and agrees well with water level measurements made in the field. Because of concerns that large-scale withdrawals of water from the aquifer would cause decreased streamflow, the model was optimized to simulate the effects on the streams with the largest streamflows: Blue River and Pennington Creek. Model simulations of the effects of distributed withdrawals on daily streamflow show that increasing withdrawal of groundwater from the aquifer would result in reduced streamflow and in reduced discharge to streams and springs in many locations.

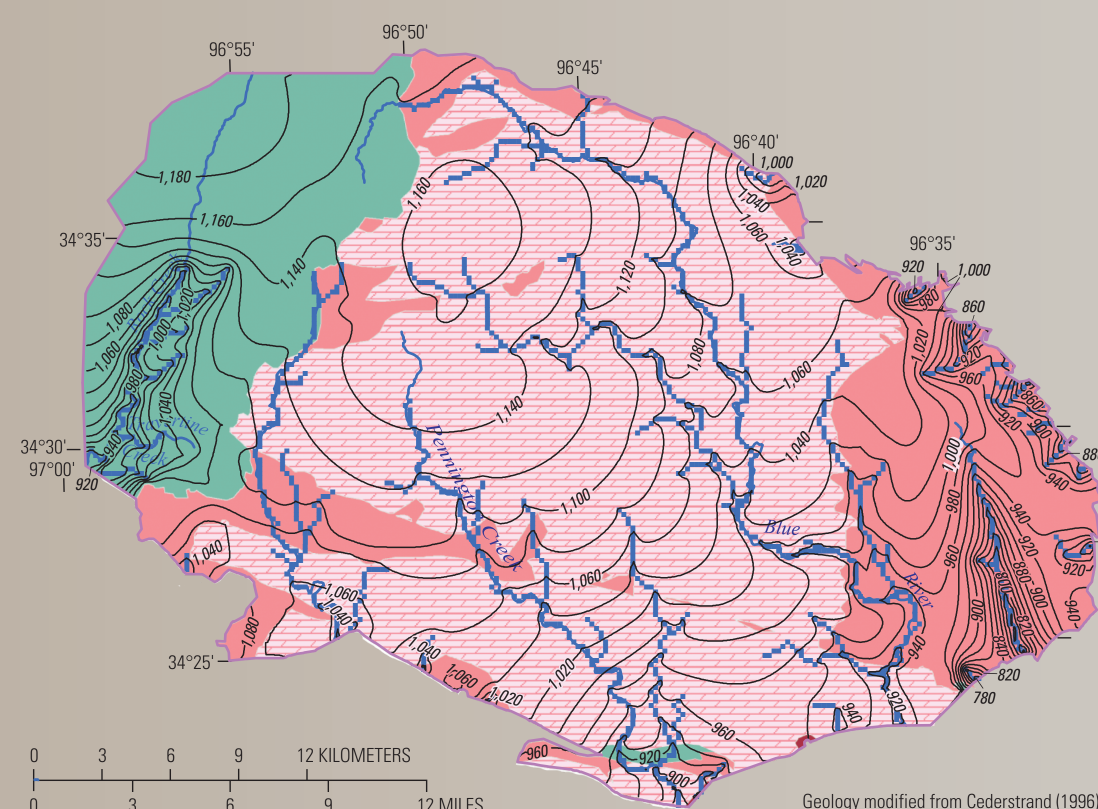

Figure 9. Simulated steady-state potentiometric surface in MODFLOW layer 1 of the Hunton anticline area (modified from Christenson and others, 2011).

Acknowledgments

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