Three-Dimensional Geologic Model of the Barton Springs Segment of the Edwards Aquifer, Central Texas

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ABSTRACT

Three-dimensional (3D) visualization models are an effective tool for evaluating and communicating the complexity of an aquifer system. The Barton Springs/Edwards Aquifer Conservation District constructed a regional 3D geologic model focused on the Edwards Group and underlying Glen Rose Formation within the Balcones Fault Zone of Central Texas. The goals of this project are to support scientific evaluations and to create an engaging and easily interpretable format for decision-making and public consumption of information.

About 730 geologic control points were compiled from driller's logs, borehole geophysics, geologic outcrops, and published geologic maps and cross sections. The data were formatted and imported into proprietary 3D visualization software. The software interpolates the point data into surfaces and then volumetric polygons. Satellite images and other geographic features were overlaid onto the model's land surface. Hydrologic data such as wells and a time series of potentiometric surfaces are integrated into the model.

The results presented here are the initial phase of an ongoing project 3D modeling project. The 3D model developed in this phase is a visually appealing regional 3D geologic model that closely matches published geologic maps and cross sections. Faults are not explicitly modeled, yet the modeled formations reflect major faulting. The model is an important regional tool for evaluating structural and hydrologic features such as the relationship of the Edwards and Trinity aquifers, Edwards Saline Zone, impacts of drought on water levels, and groundwater divides. Output from the model can be freely and readily distributed and viewed by the general public.

INTRODUCTION

The Barton Springs segment of the Edwards Aquifer provides water for about 60,000 people and Barton Springs is the only known habitat for the endangered Barton Springs Salamander. The Barton Springs/Edwards Aquifer Conservation District (BSEACD) is mandated to preserve and protect the groundwater resources within its jurisdictional boundaries. To help achieve that goal the BSEACD conducts hydrogeological research to help decision-makers make policy, and to help the general public understand the science supporting those policies. The Board of Directors (Board) for BSEACD expressed a goal of producing and communicating the best science available. However, the complexity of hydrologic issues often makes it a challenge to communicate with a non-technical audience using 2D maps and figures. An effective tool for understanding and communicating the complexity of an aquifer system is 3D visualization models. The primary obstacles to constructing 3D geologic models are the expense of software (or consultants) and expertise in using that software. District staff utilized proprietary 3D visualization software (Mining Visualization Software® [MVS] by C-Tech Corporation).

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The purpose of this paper is to describe the data, tools, and process used to construct a realistic regional geologic framework for the area defined in Figure 1. By establishing a geologic framework, subsequent datasets such as water levels or hydrochemical facies can be evaluated and displayed in its geologic context. The overall goals of this project are to support scientific evaluations and to create an engaging and easily interpretable format for decision-making and public consumption of information, outreach and education.

The results presented here are the initial phase of an ongoing project 3D modeling project. The 3D model developed in this phase is a visually appealing regional 3D geologic model that closely matches published geologic maps and cross sections. The model can be an important regional tool for evaluating structural and hydro-

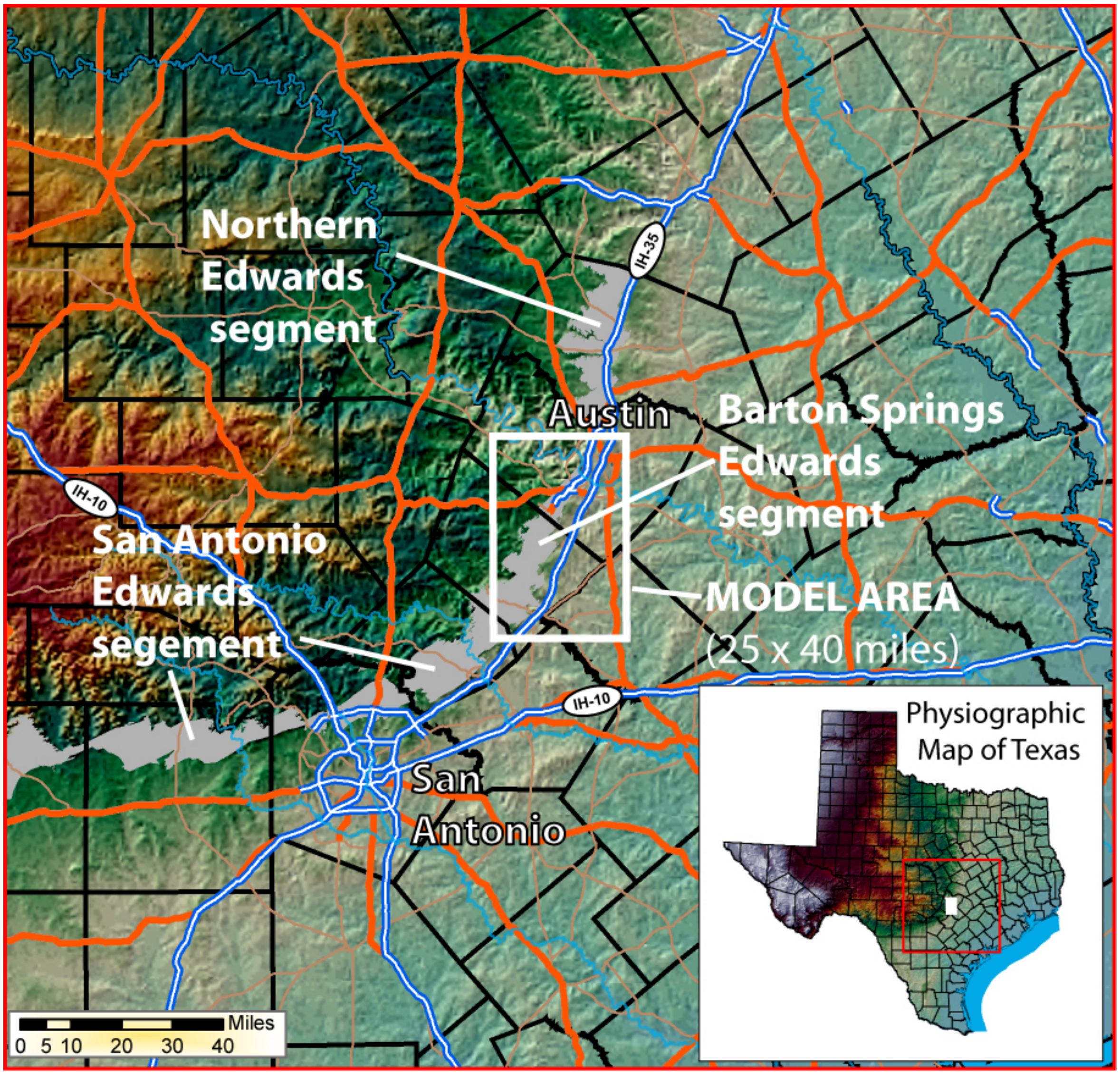

Figure 1. Overview of the region including Edwards Aquifer (shaded gray), major roads and highways, rivers, shaded topography, major metropolitan areas, and the extent of the model study area. The modeled area is about 1,000 square miles. The shaded relief map indicates relatively low elevations as "cool colors" (light blue and greens) and higher elevations as "hotter" colors (reds). The abrupt change from west to east in colors (light blue to dark green) denotes the Balcones Fault Zone and is coincident with the location of the Edwards Aquifer. Data provided by TNRIS (Texas Natural Resources Information System) and BSEACD.

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logic features such as the relationship of the Edwards and Trinity aquifers, Edwards Saline Zone, impacts of drought on water levels, and groundwater divides. Output from the model can be freely and readily distributed and viewed by the general public.

Geographic and Hydrogeologic Setting

Figure 1 shows the model area in relation to the major physiographic features of Central Texas. The model area lies along the Balcones Escarpment defining the eastern margin of the Texas Hill Country (Edwards Plateau) and the western margin of the rolling Blackland Prairies of Central Texas. Land surface altitudes increase abruptly at the escarpment, rising several hundred feet. The Balcones Escarpment is formed by the Balcones Fault Zone (BFZ), a system of northeast-trending normal faults. The geographical extent of the model includes portions of both the Edwards and Trinity aquifers. The Barton Springs segment of the Edwards Aquifer is covered in its entirety by the model, including a substantial part of the (eastern) saline zone. In addition, the model extends to the south and includes a portion of the San Antonio segment of the Edwards Aquifer including San Marcos Springs. Portions of the upper and middle Trinity Aquifers are also contained within the model. The reader is referred to Ryder (1996) and Lindgren et al. (2004) to provide detailed and regional information on the Edwards Aquifer. Detailed and regional information on the Trinity Aquifer is presented in Barker et al. (1994).

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Stratigraphy

The geologic framework of the Edwards and Trinity aquifers in Central Texas has been well described in various papers in recent decades (Brune and Duffin, 1983; Maclay and Small, 1986; Barker and Ardis, 1996). Geologic units within the model are Cretaceous limestone and dolomite with lesser amounts of marl, sand, and shale. Within the study area, the Edwards Aquifer is composed of the Cretaceous Edwards Group (Kainer and Person formations) overlain by the Georgetown Formation. These units are comprised of limestone and dolomite. Rose (1972) defined several informal stratigraphic members of the Edwards Group, each having distinctive hydrogeologic characteristics that were later mapped by Small et al. (1996). However, for the purposes of this model the Edwards Group and Georgetown Formation were lumped into one geologic unit in the model and referred to as the Edwards Group. Overlying the Edwards Group are a numerous Cretaceous limestone and shale units that provide a thick hydraulically confining package of rock. These units were lumped as one geologic unit in the model and referred to as post-Edwards units.

The Trinity units are stratigraphically below the Edwards Group and are composed of (from stratigraphically highest to lowest) the Upper Glen Rose, Lower Glen Rose, Hensel Sand, Cow Creek Limestone, and the Hammett Shale. Only the Upper and Lower Glen Rose were modeled in this study and consist mostly of limestone, dolomite, shale, and marl. Some units of the Upper Glen Rose contain evaporates.

Structure

Studies of structures along the BFZ (Collins, 1995; Collins and Hovorka, 1997) indicate that much of this area consists of southeast dipping, *en echelon*, normal faults with throws of as much as 850 ft. Most faults trend north and northeast and are downthrown to the southeast, with total vertical displacement of about 1,100 ft across the area. Some of these faults are continuous over many miles, while others extend only a few miles or less. As a result of faulting and erosion, the aquifer ranges from about 450 ft at its thickest along the east side to 0 ft along the west side of the recharge zone (Slade et al., 1986).

DATA AND METHODS

All data used in the BSEACD geologic model use the Universal Transverse Mercator (UTM) coordinate system zone 14 North (N) and the North American Datum of 1983 (NAD83). All units vertical and horizontal are in meters. The UTM system is a grid based method of encoding geographic location. It is a projected coordinate system that divides the earth into a series of sixty zones each spanning six degrees of longitude. Each zone uses a specifically defined Transverse Mercator projection with a central meridian based in the center of the zone. This system is the native projection and coordinate system of many of the publicly available datasets applicable to the study and all of the Barton Springs Edwards Aquifer Conservation Districts in-house geographic information system (GIS) datasets. The UTM coordinate system is very well suited to large scale mapping projects such as the this geologic model. It was also recommended by the creator of the modeling software being used as a good choice of projections.

Most of the effort to develop a 3D geologic model is devoted to data compilation and preparation. Data collected for the model can generally be divided into surface and subsurface categories

Surface Data

U.S. Geological Survey National Elevation Data(set) (NED) DEMs (Digital Elevation Models) at 30 m (~98 ft) grid resolution were used for the elevation surface of the model. Multiple NED datasets were needed to cover the study area. These were merged together and clipped based on the area of interest to eliminate excess processing and storage. The DEM was re-sampled from 30 m (~98 ft) to 100 m (~328 ft) and 300 m (~984 ft) to match more closely the scale of the model and to reduce processing time when developing the model. These data were used to truth the ground surface elevations of the model and help assign an elevation value to map derived geologic contacts.

Surface geology maps used include the Geologic Atlas of Texas (Pearson, 2007), Geologic Map of the Barton Springs Segment of the Edward Aquifer (Small et al., 1996), U.S. Geological Survey Edwards Aquifer Recharge Zone Geology Map (Blome et al., 2005), and a local Geologic Map of the Austin Area (Garner et al., 1992). These maps were used to define control points along key geologic contacts. These maps also helped vet the results of the model as different parameters were changed.

Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data were downloaded from the U.S. Geological Survey Global Visualization Viewer (GloVis) website (USGS, 2010). The ETM+ instrument onboard the Landsat 7 satellite collects radiation reflected and emitted from the surface of the earth in eight spectral bands. For the purposes of the model a false color infrared composite image was created using the green (0.52-0.60 µm, band 2), red (0.63-0.69 µm, band 3), and near infrared (0.76-0.90 µm, band 4) bands. Data from the panchromatic (0.52-0.90 µm, band 8) band were then overlaid on the composite image and set within the GIS software to be 80% transparent. The resultant image was exported out of the GIS software as a Geostationary Earth Orbit Tagged Image File Format (GeoTIFF) file and overlaid on the geologic model to make the orientation and general geographic setting of the model more readily apparent to the casual viewer.

Shapefiles of county boundaries and roads were downloaded from the Capital Area Council of Governments (CAPCOG, 2010) and Texas Natural Resources Information System (TNRIS, 2010) websites, respectively. These geographic datasets were used to help viewers orient themselves on maps and in presentations.

Subsurface Data

Most of the subsurface data were derived from the BSEACD's existing geologic control point database (BSEACD, unpublished), although a substantial effort was made to collect new data to fill in data gaps in the study area. Data types for the BSEACD database include geophysical logs, driller's logs, and mapped point features and contacts. Known thicknesses of units were applied to well-constrained surface and subsurface contacts to generate additional subsurface control. For example, total Edwards Group (Georgetown and Edwards) Aquifer thickness of 500 ft was subtracted from the elevation of the mapped contact of the Georgetown and overlying Del Rio Clay to obtain the base of the Edwards Group. Additional contacts were derived from the known thickness of the Upper Glen Rose (450 ft) and Lower Glen Rose (270 ft) (BSEACD, unpublished).

Modeling Approach

Previous 3D models have been developed in similar settings (Waiting et al., 2003; Pantea and Cole, 2004). The basic modeling approach was to collect and format the data into an established hierarchy, build the grid of the model, and then interpolate the data into surfaces and volumes. The overall approach was to build a layered geologic model that does not discretely model faults. The elevation surface was then used to cut the geologic layers and create a realistic surface expression of the model.

Geologic data are formatted into a special American Standard Code for Information Interchange (ASCII) text file that functions as the basic framework for building the model. The text file hierarchically lists all of the geologic units present at a sample location. Each sample location represents one geologic control point. Over 1000 geologic control points were initially collected and of these about 730 were vetted, compiled, and used in this file. Once this text file has been created it is imported into the 3D visualization software (MVS) The user verifies the hierarchy of the geologic units present in the model. MVS interpolates the data in three dimensions to create the basic geologic volumes that do not reflect ground surface elevation. This is especially in environments with a high frequency of topographic variation, such as the Central Texas Hill County along the Balcones Escarpment. To correct this problem ground surface elevation for all of the geologic control points used were shifted upward by 50 m (~164 ft) so that no point on the model's artificial ground surface was below its actual measured elevation. This artificially high surface was then made to conform or "cut" with a U.S. Geological Survey NED-based DEM of the study area.

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RESULTS

The results of this modeling effort are a visually appealing regional 3D geologic model that closely matches published geologic maps and cross-sections (Figs. 2-4). Figure 2 illustrates the close agreement of the 3D model's outcrop of the Edwards Group (plus the Georgetown Formation) and the official recharge zone boundary of the Edwards Aquifer. Figure 3 shows a comparison of cross sections along a similar line of section generated by the 3D model and a hand-drawn cross section (modified after Hauwert et al., 2004). Faults are not explicitly modeled, yet the modeled formations reflect major faulting (Fig. 3). Figure 4 is the 3D model in its entirety. Figure 5 is a close-up image of the model in map view and an oblique view with a cross section. The model provided some new insights into the hydrogeology of the region related to potential discharge points for the middle Trinity aquifer. In Figure 5A, upper-left corner, the Lower Glen Rose is exposed along the Colorado River in the 3D model. Published geologic maps (Rodda et al., 1970; Pearson, 2007) only show limited exposures due to the presence of Lake Austin. The 3D model shows more subaqueous exposures of the Lower Glen Rose along the Colorado. Once the geologic framework was built, it is relatively simple to display and view hydrologic data within the model. Figure 6 contains a series of model images that include displaying a potentiometric map for the Edwards Aquifer.

SUMMARY AND CONCLUSIONS

The model is an important regional tool for evaluating structural and hydrologic features such as the relationship of the Edwards and Trinity aquifers, Edwards Saline Zone, impacts of drought on water levels, and groundwater divides. Both scientists and the general public can explore the geologic and hydrogeologic information from any perspective allowing new insight and possibly understanding. Practical applications for using this model therefore include both visual and quantitative efforts. Output from the model can be freely and readily distributed and viewed (with a free 3D viewer) by the general public.

Era	System	Provincial Series	Provincial Stage	Stratigraphic unit	Hydro-stratigraphy	3D Model units
Mesozoic	Cretaceous	Upper / Gulfian	Navarroan	Navarro Group	Confining Units and local aquifers	Confining Group
			Tayloran	Taylor Group		
			Austinian	Austin Group		
			Eaglefordian	Eagle Ford		
		Upper / Comanchean	Washitan	Buda Limestone		
				Del Rio Clay		
		Lower / Comanchean		Georgetown Formation	Edwards Aquifer	Edwards Group
				Edwards Group: Person Formation		
			Fredericksburgian	Edwards Group: Kainer Formation		
			Trinitian	Glen Rose Limestone: Upper	Upper Trinity	Upper Glen Rose
				Glen Rose Limestone: Lower	Middle Trinity Aquifer	Lower Glen Rose
				Pearsall Fm: Hensel Sand Mbr (Bexar Shale Mbr)		These units were not modeled
				Pearsall Fm: Cow Creek Mbr		
				Pearsall Fm: Hammett Shale Mbr (Pine Island Shale Mbr)	Confining Unit	
				Sligo Fm	Lower Trinity Aquifer	
				Hosston Fm		
Paleozoic				Undifferentiated rocks of the Ouachita Structural Belt		

Figure 2. Stratigraphic and hydrostratigraphic column of the study area (modified after Barker and Ardis, 1996). The 3D geologic model simplifies the diverse geology into four model units as shown.

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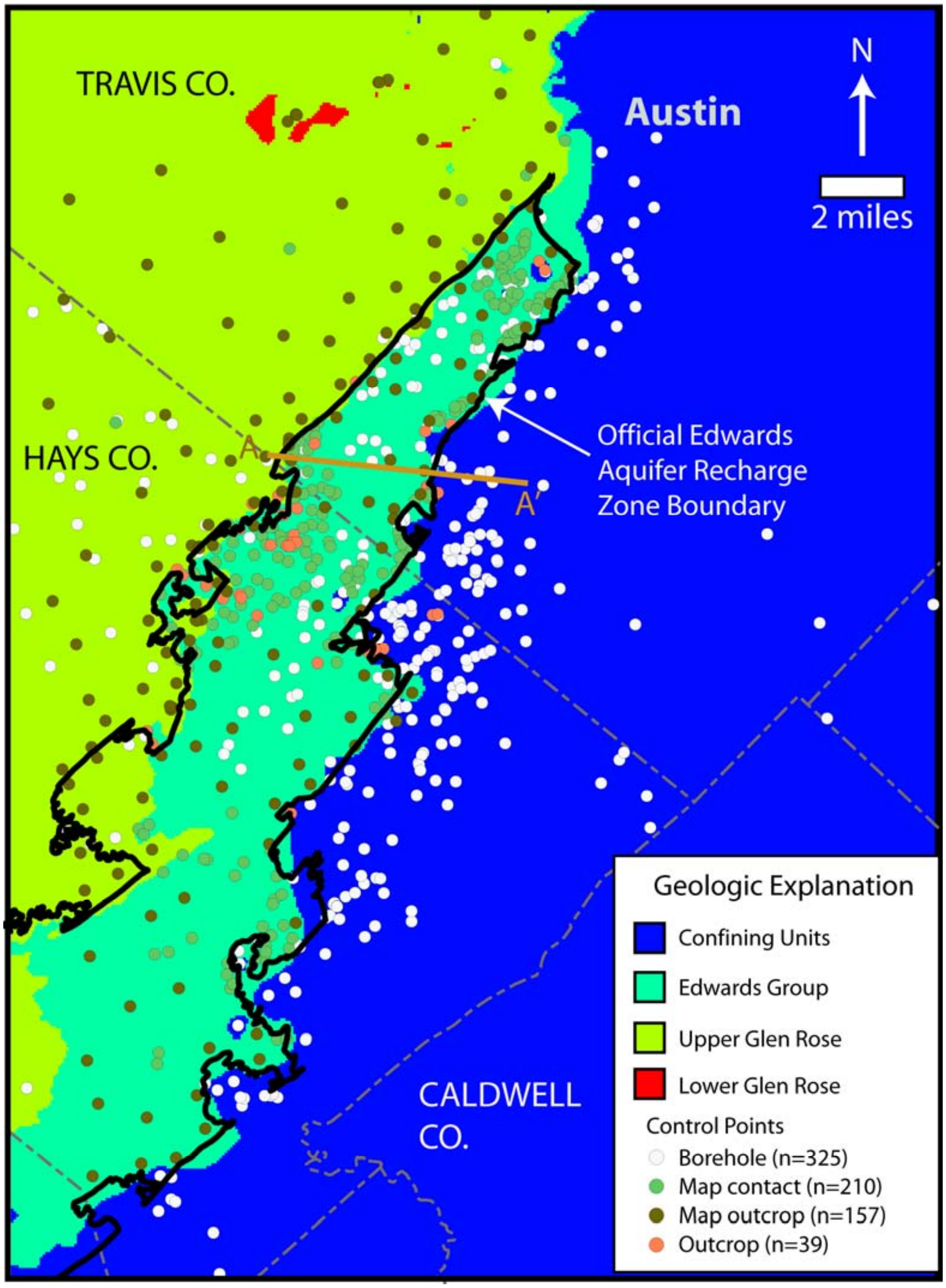

Figure 3. Map illustrating the surface geometry of the 3D model. The blue, green and red background image in this figure is a two dimensional map view of the surface geology as generated by the 3D model. The black line is the Texas Commission for Environmental Quality recharge zone boundary of the Edwards Aquifer. Grey dashed lines are county boundaries and the multicolored circles represent geologic control points used to construct the model. The figure helps illustrate where the 3D model closely follows mapped exposures of the Edwards Group and where more data may be needed for a better match.

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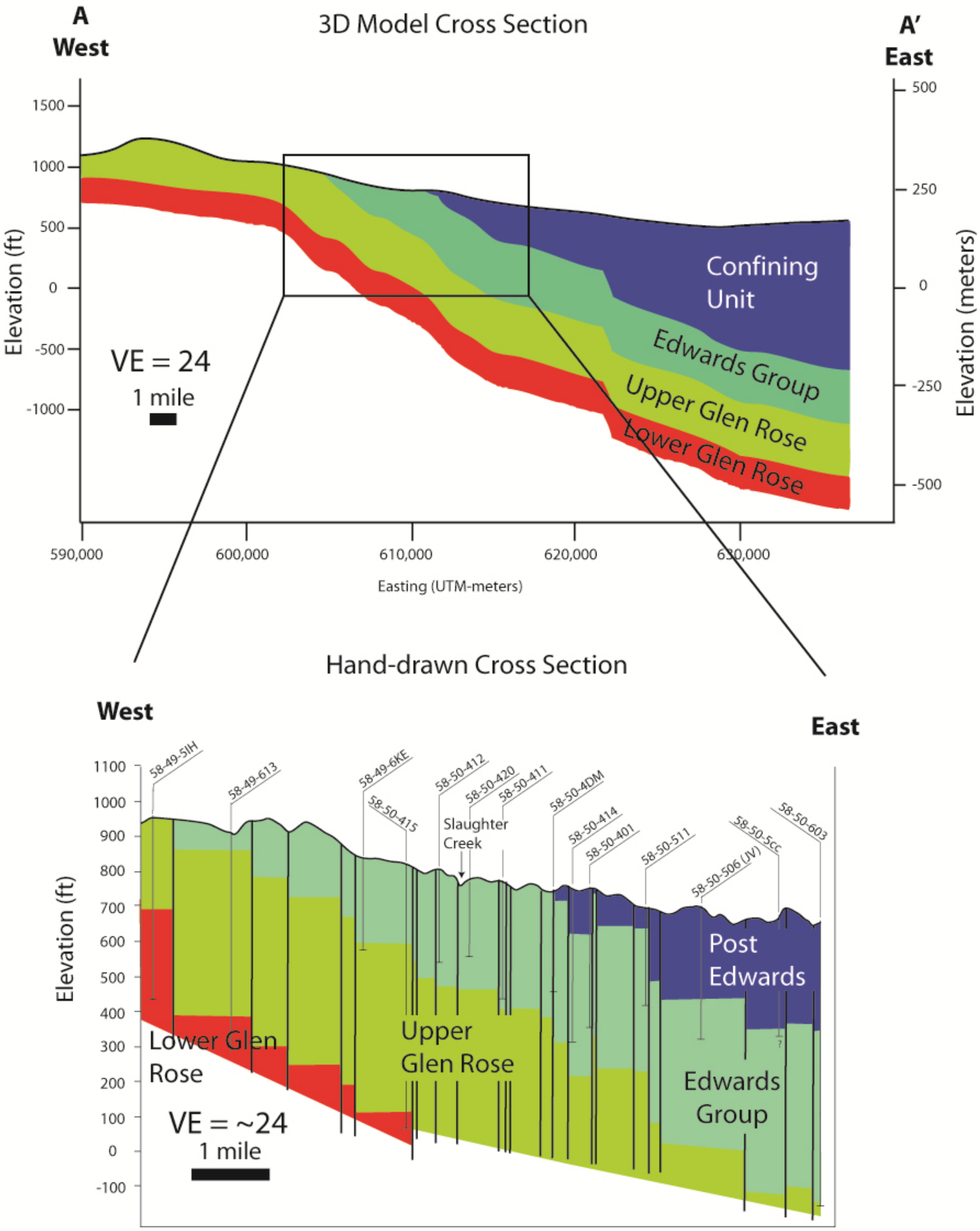

Figure 4. Two cross sections illustrating the study area geometry and demonstrates the accuracy of the 3D model across the study area. The top cross section was derived from the 3D model, and the bottom section was hand drawn based on 14 boreholes. The location of the cross section A-A' is located on Figure 3.

FUTURE WORK

This model represents an initial phase of a regional geologic model and will be the starting point for future models containing more detailed information. It is currently planned that this will be accomplished in an incremental fashion by dividing the study area into smaller segments based on major fault blocks. These fault blocks would be modeled more precisely and include more geologic units, and also possibly hydrostratigraphic subdivisions. Like pieces of a puzzle as each fault block is finished it will be merged appropriately with other finished fault blocks. In this fashion a more accurate and detailed picture of the study area will take shape over time. It is also a goal of the modeling team to incorporate diverse data sets such as specific caves, dye tracing study results and water chemistry into the three dimensional setting of the model. MVS models which are capable of quantitative analysis using the volumetric functions.

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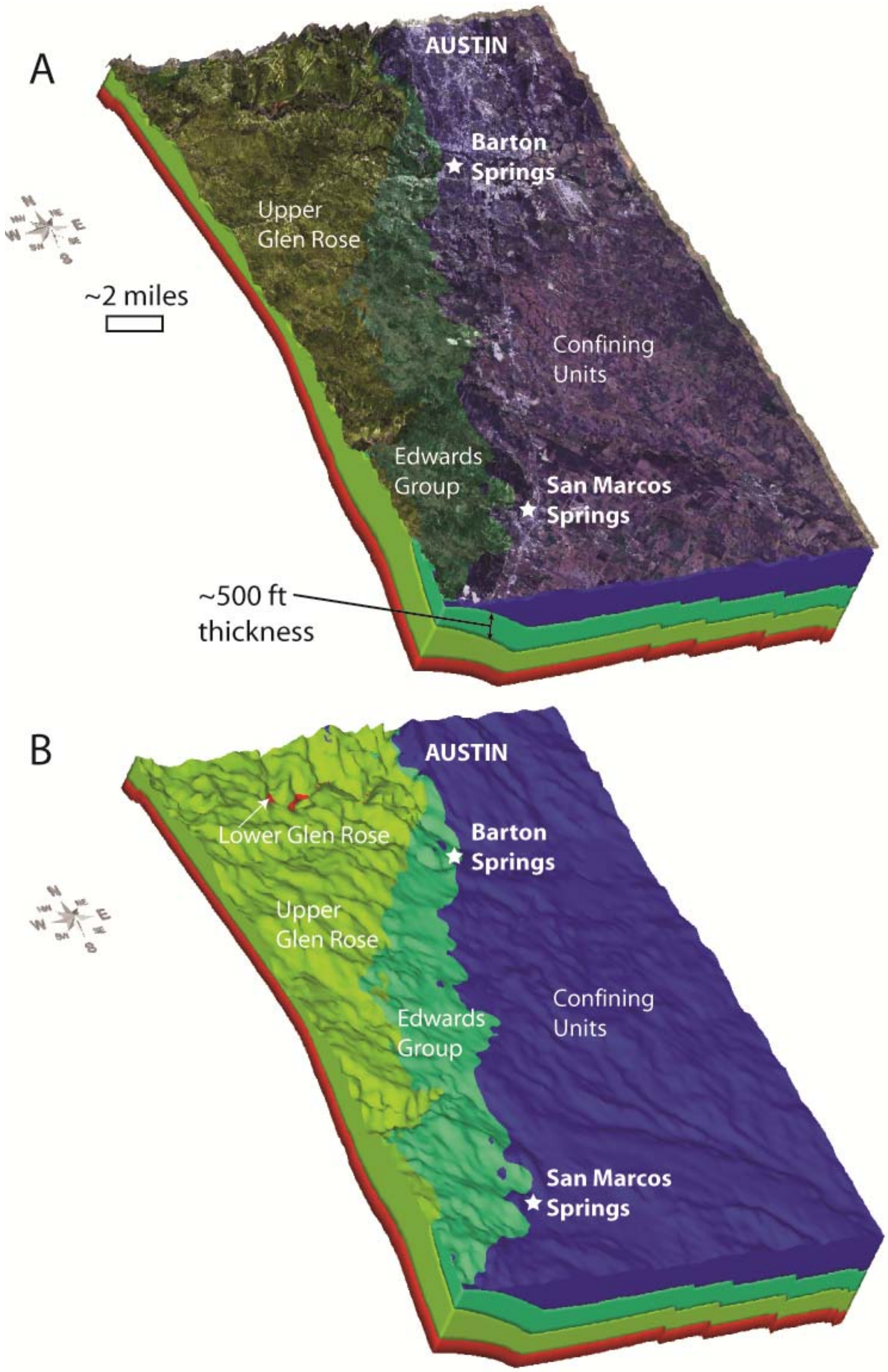

Figure 5. (A) Screen capture of the model from an elevated perspective to the southwest with satellite image overlaid and 50% transparent. (B) Same image as top but with satellite overlay turned off and features labeled.

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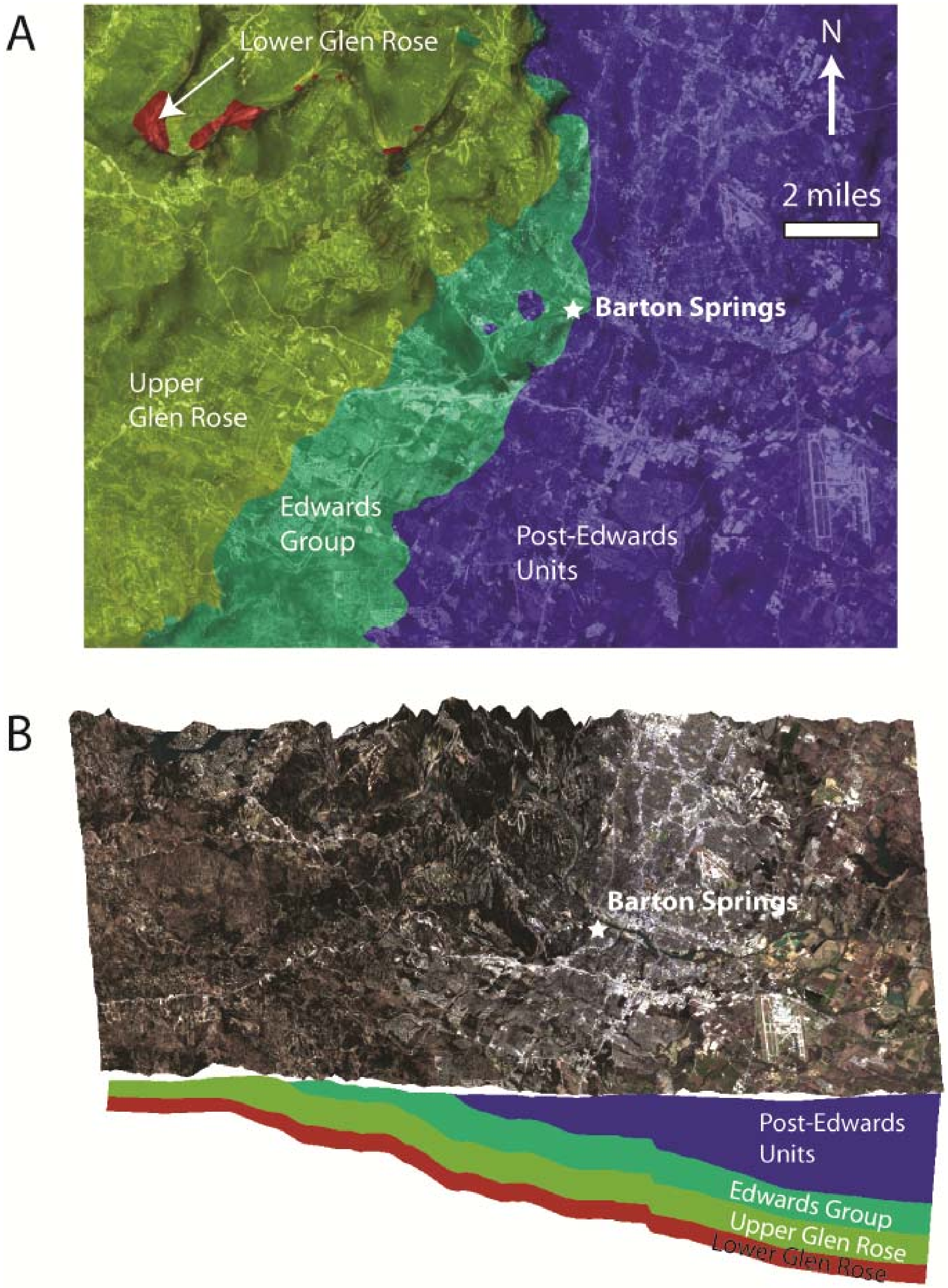

Figure 6. (A) Screen capture centered over the north-central area of the 3D model area. The semi-transparent geology overlays the satellite image and highlight possible locations where the Lower Glen Rose is exposed. (B) Screen capture of the same area as top but rotated on its side to make the subsurface cross section visible and topography more apparent.

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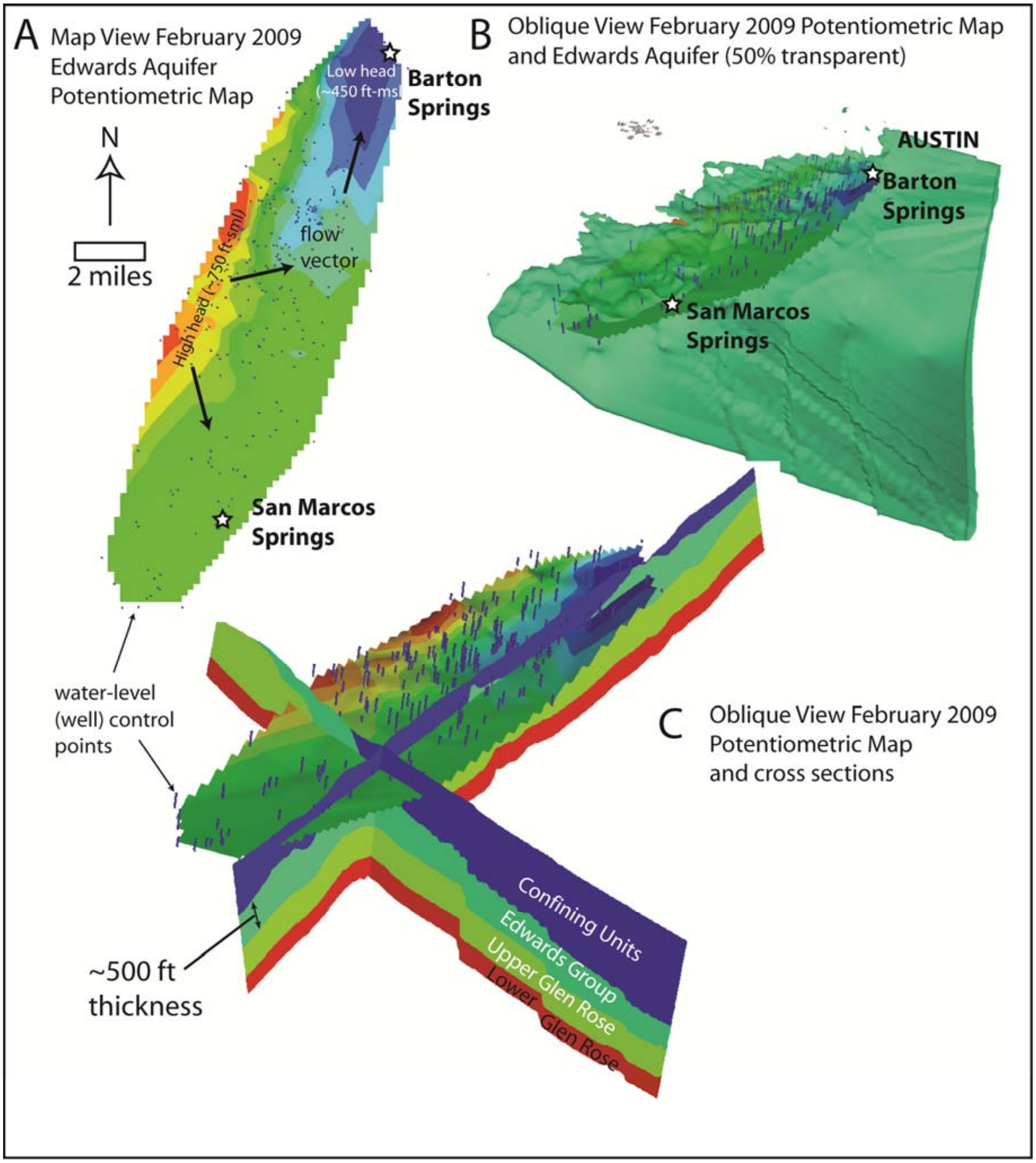

Figure 7. A collection of figures showing the application of the model to view a potentiometric surface map in relation to the geologic framework. (A) Screen capture of the map view of the February 2009 potentiometric map with water-level control points. Color shading is 50 ft intervals and range from about 750 ft above mean sea level (msl) (reds, oranges) to low heads low heads of about 450 ft msl (blue colors). (B) Oblique view of the potentiometric map shown in relation to the Edwards Group (50% transparent). (C) Oblique view of the potentiometric map in relation to two intersecting geologic cross sections.

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