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Three-Dimensional Geologic Model of the Pecatonica Gas Storage Field, Winnebago County, Illinois

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Abstract This study involves the construction of a three-dimensional (3D) geologic model of Paleozoic strata that are part of an underground gas storage field in northern, Illinois, USA. The Pecatonica Anticline trends 60W and plunges gently to the southeast. It is 10 km long and 3 km wide, and verges to the NE. Six water wells and 22 gas wells were used to create the 3-D geologic model in *Petrel* using well tops as determined from wire-line logs. The following horizons were created for the Cambrian and Ordovician strata: the Ancell, Trempealeau, Franconia, Ironton-Galesvilles, Eau Claire Proviso A and B, Eau Claire Proviso C "Ligthsville (top), and Eau Claire Proviso C "Lightsville (bottom). The horizons, edges, and intersections were then color-coded and an initial model was created. In the model area, the "Lightsville", which is the principal layer used for gas storage, has about 10 m of closure over 0.80 Km^2 with a volume 199x10-3 km^3. No faults or other structural discontinuities that may influence gas migration are evident in the model area.

Keywords: *ordovician, cambrian, illinois, gas storage, three-dimensional geologic model, petrel*

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1. Introduction

In Winnebago County, IL, an underground natural gas storage field is present southeast of the town of Pecatonica (Figure 1). This is one of several such facilities in Illinois, where natural gas is stored in deep Cambrian and Ordovician sandstones present in broad anticlinal structures [1,2]. With the growth in development of Boone and Winnebago counties (i.e. greater Rockford metropolitan area), there is a need for a better understanding of the structure and stratigraphy of these storage fields to ensure optimal management.

Natural gas (methane) is stored within a deep saline aquifer until it is needed in the winter heating season. Underground gas storage fields in the upper Midwest are essential to meet the energy demands of the winter heating season. During summer months, gas is transferred by pipeline from the Gulf Coast and is then injected into deep saline aquifers [3]. The gas is withdrawn during the winter. Accurate and detailed geologic information is essential for engineers to manage properly these storage fields.

Worldwide, there have been numerous studies on a variety of underground gas storage facilities over the past several decades [2,4-10]. In Illinois, however, few recent studies have focused on dozens of gas storage [11,12]. Some hydrogeologically-focused research has focused on the Pecatonica area [13,14,15,16], but there has no detailed structural or stratigraphic research on the Pecatonica field.

Hydrogeologically, the Pecatonica gas storage field is unusual because of its tilted gas-water interface [17]. Ideally, the base of a gas bubble should be flat. One hypothesis credits the tilted interface from stratified water, where dense saline water underlies lighter fresh water, thus it is easier for water to move laterally rather than vertically [11]. Bond [11] hypothesizes the tilted gas interface is present as a result of a tilted potentiometric surface (Figure 2).

The purpose of this report it to provide a structural and stratigraphic three-dimensional geologic model of the Pecatonica gas storage field. The model was constructed in *Petrel* using existing well data.

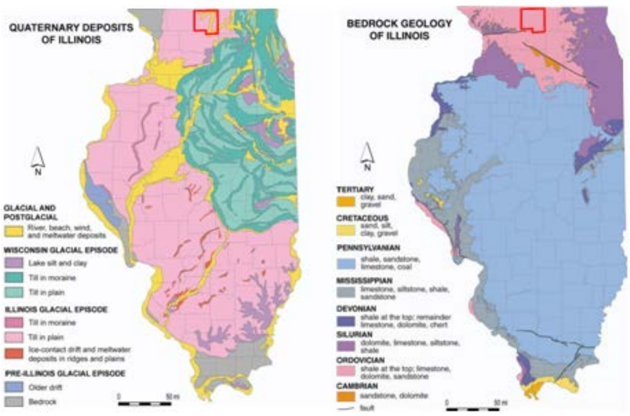

Figure 1. Quaternary and Bedrock Geologic Maps of Illinois. Winnebago County is outlined in red

2. Bedrock Geology

Ordovician and Cambrian strata comprise the bedrock geology of the area [1,18,19,20]. A stratigraphic column of bedrock strata in Winnebago County is provided as Figure 3 [1].

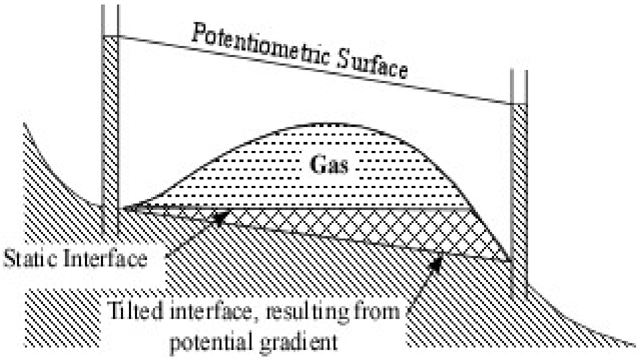

Figure 2. Schematic diagram of the tilted gas-water interface at Pecatonica (from [11])

The Galena-Platteville Groups are collectively more than 100 m in thickness and consist of layers of dolostone. The dolostone ranges from coarsely fossiliferous to micritic, and is locally cherty and/or heavily bioturbated [21]. Thin layers of bentonite are also present [22]. Most of the dolostone is fine to medium grained and have undergone various degrees of recrystallization [1]. The Platteville Group grains are typically uniform while the Galena Group has abrupt changes in grain size from fine to medium within beds.

Underlying the Galena-Platteville is the Ancell Group, which consists of the Glenwood Formation, St. Peter Sandstone, and Kress Formation. The Glenwood Formation is as approximately 18 m in thickness, and consists of interbedded shale, siltstone, and sandstone [23]. The Glenwood is best characterized as a sandy mudstone. The sand grains are medium sized and well-rounded quartz [23]. The Glenwood is not consistently present within the Pecatonica area.

The St. Peter Sandstone underlies the Glenwood and is approximately 120 m in thickness. The St. Peter is a medium to fine grained, well sorted sandstone that is friable and weakly cemented [23]. The St. Peter is a clean sandstone, free of clays, carbonates, and heavy minerals, except in local areas [23]. At the base of the St. Peter, a conglomerate unit is locally present.

The Trempealeau Group underlies the Ancell Group. The two units are separated by the sub-Tippecanoe unconformity found in Northern Illinois to occur at the base of the Ancell or St. Peter Sandstone [23]. Willman, Atherton [23] concluded the unconformity is an erosional surface that resulted from karst topography development. The Trempealeau thickness ranges from approximately 5 to 35 m. The Trempealeau is a pink dolomite that is finely crystalline, glauconitic, and at some places porous. Clay, silt, sand, chalky chert, and geodes lined with quartz are also present within this unit.

The Franconia Formation, underlying the Trempealeau, is 15 to 30 m in thickness. The formation contains interbedded shales, red and green, fine-grained, silty, sandstones and sands, and some dolomite [23]. The dolomite beds when present are primarily found near the top of the unit.

The Ironton-Galesville Group underlies the Franconia Formation. The unit is approximately 50 m thick. The two units consist of sandstone with varying textures and dolomite content [23]. The Ironton Sandstone is medium-grained, typically poorly sorted, and dolomite rich. The Galesville is a fine-grained, well sorted quartz arenite, devoid of fossils. In the northern areas of Illinois, the Ironton can be fossiliferous. Overall, the dolomite content of the Ironton-Galesville sandstone is lower in northern Illinois [14].

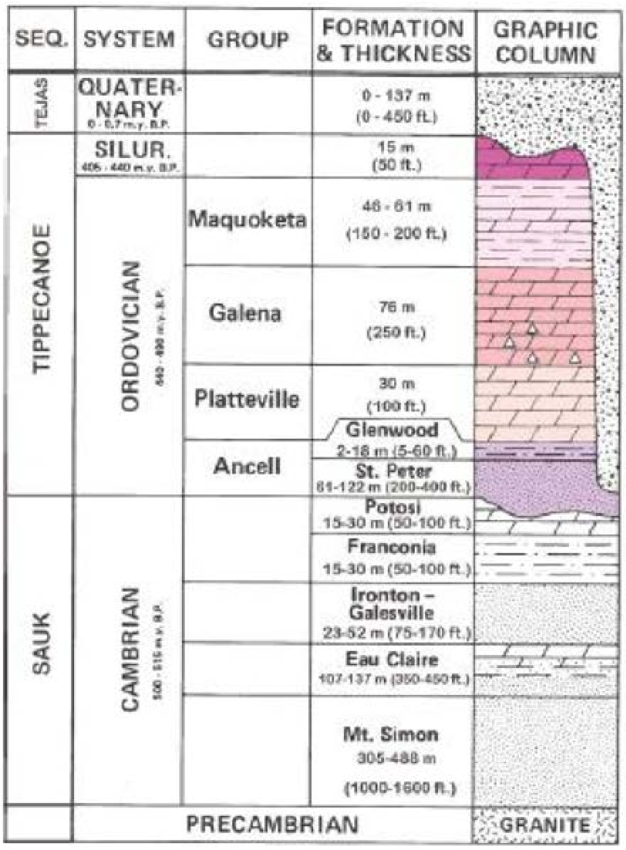

Figure 3. Paleozoic Bedrock Stratigraphy of Winnebago County (from [1])

The Eau Claire Formation underlies the Ironton-Galesville. This unit is Cambrian in age and divided in two three members. The Eau Claire formation is a light yellow-brown to gray, very fine to course grained locally silty, dolomite or argillaceous sandstone with lesser quantities of dolomite to silty variegated shale, sand dolomite, and siltstone. The Eau Claire is approximately 105 m to 135 m in thickness. The three members that divide the Eau Claire formation include the top most member, the Proviso Member, underlain by the Lombard Member, and the Elmhurst Member, which creates the base of the formation. The Proviso is further divided into three sections, A, B, and C. The upper 12 m of the Proviso Member A is fine-grained shale and dolomitic sandstones [13]. The Proviso Member B is composed of interbedded shales, dolomites, and sandstone.

The Proviso A and B unit thickness ranges from 18-20m. The middle part of the Eau Claire formation, the Proviso C “Lightsville” section, consists of white to light gray friable sandstone (Deters, Pers. Com.). The Lightsville is approximately 25 m in thickness. It can be silty to clean, very fine to coarse-grained, generally better sorted than the Lombard member, which underlies the Proviso Member of the Eau Claire Formation. The Lombard Member contains interbedded white, dense dolomites and sandy argillaceous dolomites. The lower most member of the Eau Claire, The Elmhurst Member is a very porous white and clean sandstone [13,14]. The Elmhurst grades to the Mt. Simon sandstone. The Mt. Simon sandstone is a poorly sorted, very fine to very coarse-grained white to red, silty, friable sandstone with local areas of conglomerate. The Mt. Simon is also Cambrian in age. Its thickness ranges from 300 to 500 m.

3. Bedrock Structure

The regional structure is flat lying or gently dipping to the south The Pecatonica Anticline was first described by Buschbach and Bond [12]; it trends about N60W, and plunges gently to the southeast. It is 10 km long and 3 km wide, and verges to the NE. Dips of 5-10 degrees can be measured at bedrock exposures in the local quarries.

Thirty gas storage wells penetrate the Proviso C “Lightsville” Member of the Cambrian Eau Claire Formation [20]. The Eau Claire Formation is not exposed at the surface. The Proviso is approximately 250 meters underground at the crest of the structure (Figure 4).

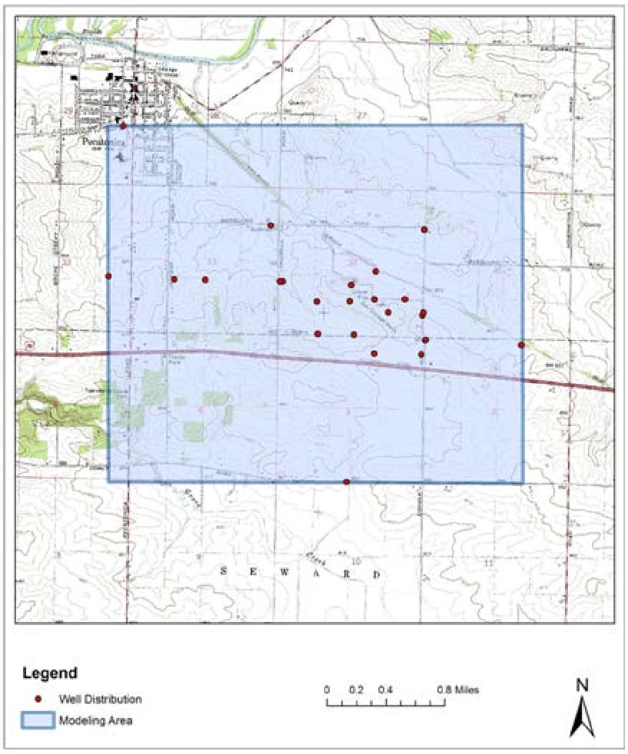

Figure 4. 3-D modeling area with well locations

4. Methodology

Petrel [24] is a computer program developed by Schlumberger Inc. This program is utilized by the oil and gas industry for fault modeling, stratigraphic analysis, reservoir engineering, among other analyses [22,25]. Overall, Petrel helps to solve uncertainties in subsurface reservoirs and works to improve reservoir quality predictions

Data used in this model includes only well data. First, water well data of Winnebago County were acquired. These well records were obtained from the Illinois State Geological Survey ILWATER and ILOIL databases. The well data were used to build the 3-D geologic model: section, township, range information, well log descriptions, and Gamma Ray and Neutron logs. The latitude and longitude of each well was acquired from the ISGS Oil and Gas Resources (ILOIL) Internet Map Service website. Occasionally, a specific depth or elevation of one unit was missing from the database. In such cases, the original gamma ray and neutron logs were analyzed to determine the stratigraphic position of the unit.

In total, six water wells and 22 gas wells were used to create the 3-D geologic model. Well distribution over the study area was concentrated around the highest point of closure of the anticline but were more sparse surrounding the structure (Table 1; Figure 4). The following units were included in the 3-D geologic model in lithostratigraphic order: Ancell, Trempealeau, Franconia, Ironton-Galesville, Eau Claire Proviso A and B, Eau Claire Proviso C “Lightsville” (top), and Eau Claire Proviso C “Lightsville” (bottom).

Using *Petrel*, a new project and well folder were created to begin the 3-D geologic model. A text file including the well name, X,Y data, top elevation, and total length of the well was inputted into the well folder in Petrel under the name of “well heads.” Then a “well tops” folder was created. Each unit’s (Ancell, Trempealeau, Franconia, Ironton-Galesville, Eau Claire Proviso A and B, Eau Claire Proviso C “Lightsville” (top), and Eau Claire Proviso C “Lightsville” (bottom) text file was imported into “well tops” folder. The text file information added for each unit is displayed in *Petrel* as a series of points that make up the well layers (Figure 4). Each unit was created separately so it may be easier to make adjustments. If needed, the entire layer could be deleted, edited, and re-imported back into the model. Unit surfaces were then created from the “well top” point data (Figure 5). Table 1 includes all of the descriptive parameters for the *Petrel* screenshots.

Table 1. Explanation to the geology and axes for all of the Petrel Screenshots

Key:	
X-axis	UTM Zone 16 horizontal grid value
Y-axis	UTM Zone 16 vertical grid value
Z-axis	Elevation above MSL in m.
Vertical exaggeration	10
Ancell	Orange
Trempealeau	Purple
Franconia	Blue
Ironton-Galesville	Green
Eau Claire Proviso A & B	Yellow
Eau Claire Proviso C "Lightsville"	Red

Once the unit surfaces were created it was possible to generate a model. *Petrel* includes a step for adding faults, which is a step that cannot be skipped even though there are no faults in the mapping area. If no faults are present then no action was performed and the next step is executed. Before the 3-D model can be created, a grid outline the 3-D model must be generated. To develop the model grid the unit, surfaces are inputted into the “3-D model grid” window. The default interpolation method convergent interpolation, was set in the “3-D model grid” window. The following horizons were created: the Ancell, Trempealeau, Franconia, Ironton-Galesville, Eau Claire Proviso A and B, Eau Claire Proviso C “Lightsville (top), and Eau Claire Proviso C “Lightsville (bottom). The horizons, edges, and intersections were then color-coded and an initial model was created (Figure 6).

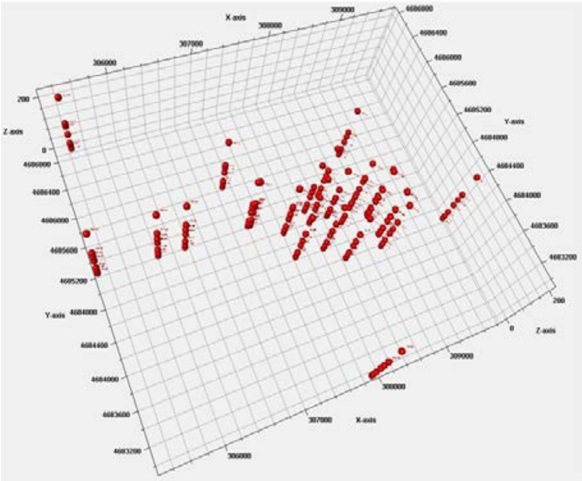

Figure 5. Petrel well top data for 3-D model

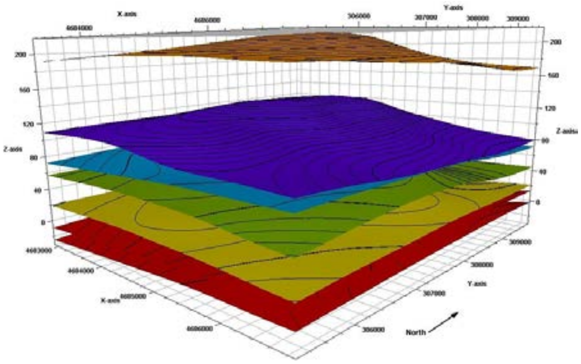

Figure 6. Initial 3-D model with geologic horizons interpreted by *Petrel*: Ancell, Trempealeau, Franconia, Ironton-Galesville, Eau Claire Proviso A and B, Eau Claire Proviso C "Lightsville" (top), and (bottom)

This model was a good start to visualizing the subsurface geology; however, it still required some refining to more effectively outline the stratigraphy and the structure. There are locations near the edges of the model where the interpolated horizon has less data. In these locations, the interpolated horizon dipped up or down. The dip in the unit horizon affected the units' thicknesses, giving the appearance that a bed may be pinching out near the edges of the model. The Trempealeau, Eau Claire Proviso A and B, and the Ancell vary in thickness as the horizon reaches the north end of the model.

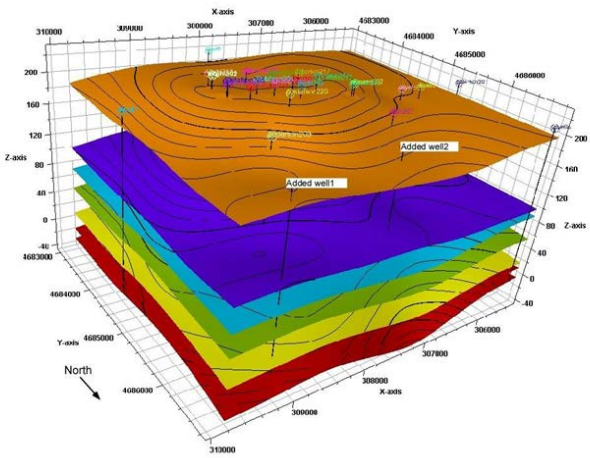

Figure 7. The second model three-dimensional model outlining the two new synthetic wells as well as the seven unit horizons: Ancell, Trempealeau, Franconia, Ironton-Galesville, Eau Claire Proviso A and B, Eau Claire Proviso C "Lightsville" (top), and (bottom)

The second model was a definite improvement because it outlined the anticline in more detail and maintained thickness for all of the unit horizons (Figure 7). To maintain thickness between the interpolated horizons, two new well were added to the model within the problem areas. "Water Well 1" data were applied to create the new wells. "Water Well 1" was chosen because its proximity to the location where the interpolated surface dipped in most of the unit horizons. The X, Y data were determined using the axes of the 3-D model. The two new wells were added into the spreadsheet and re-saved in text file form. The second model was developed with the same steps as the initial 3-D model with the new data (Figure 7).

5. Results

Once the second model was created, the estimated area and volume of anticline closure were determined for each unit except the "Lightsville base." The basal layer of the model, the Eau Claire Proviso C "Lightsville" (bottom), was generated only to help outline thickness of the unit. Moreover, the gas storage field is located near the top of the Eau Claire Proviso C Lightsville." The area and volume of the basal layer is not need because no gas is stored in the unit underlying the "Lightsville."

The final 3-D geologic model of the Pecatonica Anticline contains seven units and the added data (Figure 8). The rendition of the initial model represents the accurate location of both gas storage wells and water wells as well thickness continuity throughout the entire model. By refining the X, Y data for each of the wells, the resulting interpolated surfaces more definitely outlined the anticline in each of the interpolated horizons. The north to south cross section of the final model outlines all of the units and their thicknesses. Overall, each of the interpolated horizons maintain a continuous thickness. There are no longer units pinching out in the north side of the 3-D model.

The results of the volume and area under the anticline can be viewed in Table 2. "Lightsville" has about 10 m of closure over 0.80 km^2 with a volume $199x10^{-3}$ km^3. The Ancell has 15 m of structural closure over about 18 km^2 with a volume of about $4.50x10^{-2}$ km^3.

Table 2. Area and Volume of the closure of the anticline in each unit

Unit	Total Area km^2	Total Volume km^3
Ancell	17.98	4.50×10^{-2}
Trempealeau	1.47	3.67×10^{-3}
Franconia	7.42	1.86×10^{-2}
Ironton-Galesville	1.31	3.27×10^{-3}
Eau Claire Proviso C "Lightsville"	0.80	1.99×10^{-3}

6. Discussion and Conclusions

The final 3-D model shows the structure, stratigraphy, and the estimated thickness of the bedrock in the Pecatonica area. The anticline is clearly seen in all of the seven unit horizons of the 3-D geologic model.

The anticline contains all of the seven horizons of the final model but the extent of the anticline closure diminishes with depth. The estimated volume and area of closure under the anticline for each unit horizon in the 3-D provides insight into the overall structure of the bedrock surface and the reservoir potential. The results of the volume and area calculations from the current study found that the Eau Claire Proviso C “Lightsville” has about 10 m of closure over 0.80 Km^2 with a volume $1.99x10^{-3}$ km^3 based on the 3-D model.

The Eau Claire Proviso C “Lightsville” closure is the smallest of all of the unit horizons. This could be cause for concern for expansion of the gas storage capacity. However, while the unit may have a smaller closure, it underlays a strong cap rock, the Eau Claire Proviso A and B. The Eau Claire Proviso A and B unit consists of dolostone, shale, and a silty sandstone, which provides a stable cap rock for the storage of nature gas.

Moreover, the 3-D model found no evidence of significant faults or other structural discontinuities. Erosional incision also is not a concern since the bedrock surface is separated from the Eau Claire Proviso C “Lightsville” unit by 170 to 200 m. The bedrock units that separate the shallower unit from the Eau Claire Formation include dolostone and limestone of Trempealeau as well as shales and silty sandstones of the Franconia Formation. Thus, a significant cap of multiple units, in combination with the Eau Claire Proviso A and B dolostone cap rock will prevent possible migration to shallower units near the surface.

Overall, the 3-D geologic model of the Pecatonica Anticline is a step forward in visualizing the subsurface geology. Prior to the development of the 3-D model, only cross sections of the area were available. Now, these modeled horizons could be utilized to create new cross sections of the area and to provide more insight into the geology of the underground storage field.

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