2.0 Geology and Hydrology

The geologic and hydrogeologic properties described in this chapter are used to develop a conceptual model of the proposed CO_2 storage site in Morgan County, Illinois. The conceptual model is a fundamental part of this UIC Class VI Permit submitted by the Alliance for the construction and operation of up to four CO_2 injection wells. This chapter provides both regional and local information about the injection zone (the geologic formation that will receive the CO_2) and the confining zones (the geologic formations that will act as a barrier to fluid migration). This information is provided to demonstrate that the proposed Morgan County CO_2 storage site is a suitable geologic system for CO_2 storage, and the confining zones have sufficient extent and integrity to contain the injected CO_2 and displaced formation fluids so as to ensure the protection of nearby underground sources of drinking water (USDWs). This chapter provides background information in support of the conceptual model, which is developed in detail in Chapter 3.0. The information in this chapter is also critical to the design, construction, and operation of the injection and monitoring wells and in the subsequent well plugging after the site has completed CO_2 injections.

The regional geology, including the regional continuity of the proposed injection and confining zones, is described in Section 2.1. A site-specific description of the geology at the Morgan County CO_2 storage site—derived from a stratigraphic well that was drilled near the proposed injection in support of this UIC application—is provided in Section 2.2. This information is supported by results from other nearby wells and the published literature, which together form the basis of the description of the geologic setting of the proposed Morgan County CO_2 storage site described in Section 2.3. Geomechanical data for the proposed injection and confining zones are presented in Section 2.4. The seismic history of the region is described in Section 2.5. Site groundwater is described in Section 2.6. A site evaluation of mineral resources is presented in Section 2.7. A discussion of the wells within the AoR and the one well (stratigraphic well) that penetrates the injection and confining zones follows in Section 2.8. The conclusion in Section 2.9 demonstrates that the proposed Morgan County CO_2 storage site meets the minimum criteria for siting specified in 40 CFR 146.83(a). Note that the detailed physical and chemical properties used as input parameters to the computational model are presented in Chapter 3.0. References for sources cited in the text are contained in the final section of this chapter.

2.1 Geology

The Alliance proposes to inject CO_2 into the Cambrian-age Mount Simon Sandstone and the lower Eau Claire Formation (Elmhurst Sandstone member), which combined make up the injection zone. The Mount Simon Sandstone is the thickest and most widespread potential CO_2 injection formation in Illinois (Leetaru and McBride 2009), and at the Morgan County site (Figure 2.1). The Elmhurst Sandstone, along with the Mount Simon, is an injection zone at a number of natural-gas storage sites in Illinois (Morse and Leetaru 2005). The confining zone for the proposed injection zone consists of the Lombard and Proviso members of the Eau Claire Formation that overlies the Mount Simon and Elmhurst sandstones. The Eau Claire is the most important regional confining zone in Illinois (Leetaru et al. 2005, 2009). The Davis member of the Franconia Formation forms a secondary confining zone above the Eau Claire Formation. Impermeable Precambrian-aged basement rocks underlie the Mount Simon Sandstone and form a no-flow boundary to the conceptual model.

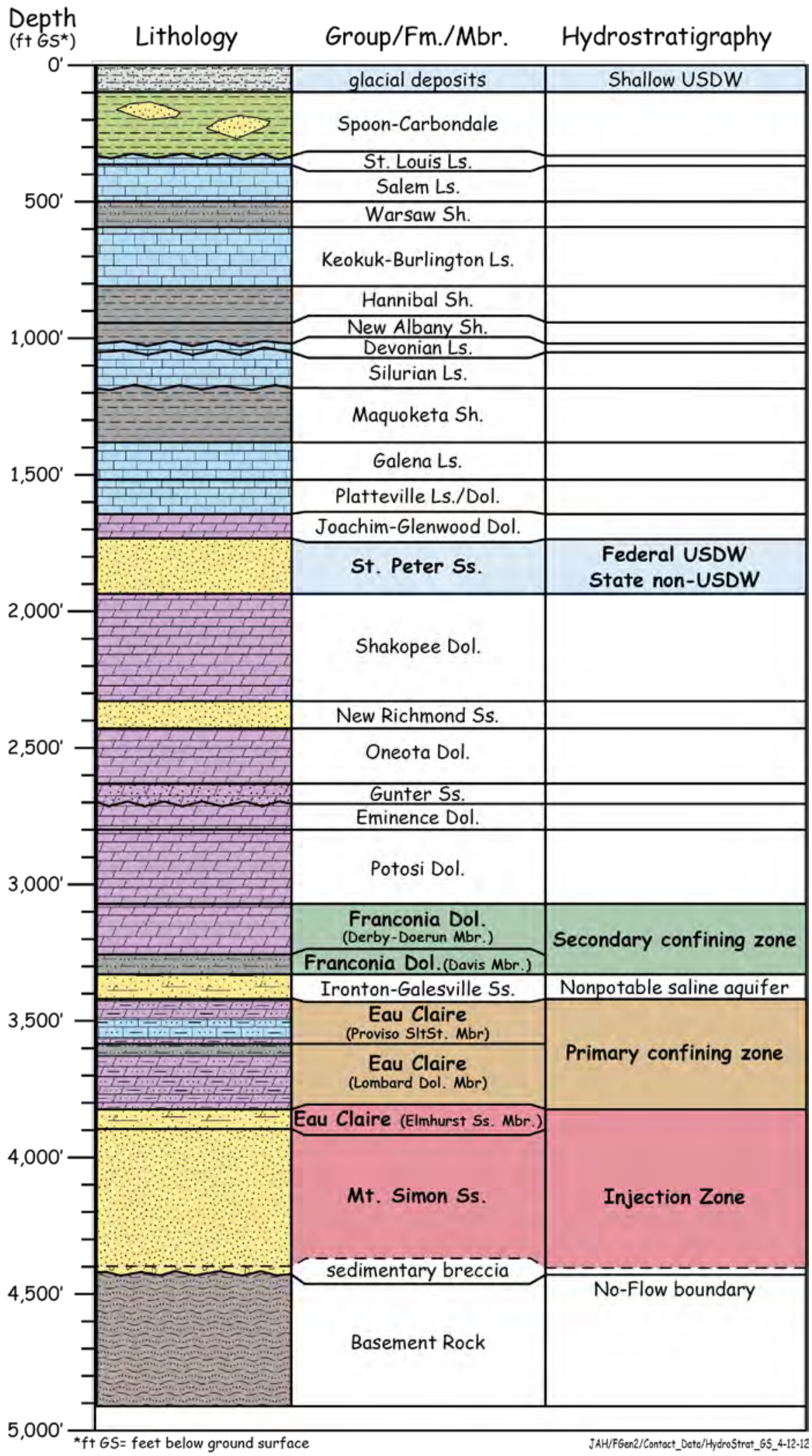

Figure 2.1. Stratigraphy and Proposed Injection and Confining Zones at the Morgan County CO_2 Storage Site

2.1.1 Regional Geology

The regional geology of Illinois is well known from wells and borings drilled in conjunction with hydrocarbon exploration, aquifer development and use, and coal and commercial mineral exploration. Related data are largely publicly available through the Illinois State Geological Survey (ISGS)[1] and the U.S. Geological Survey (USGS).[2] In addition, the DOE has sponsored a number of studies by the Midwest Geologic Sequestration Consortium[3] to evaluate subsurface strata in Illinois and adjacent states as possible targets for the containment of anthropogenic CO_2. This section describes the regional geology, including stratigraphy, structure, and seismicity.

The Mount Simon Sandstone in the Illinois Basin represents a regional target for safe injection of anthropogenic CO_2 (Leetaru et al. 2005). The Illinois Basin covers an area of about 110,000 mi^2 over Illinois and parts of Indiana and Kentucky (Figure 2.2). The Illinois Basin contains approximately 120,000 mi^3 of Cambrian to Pennsylvanian marine and terrestrial sedimentary rocks with a maximum thickness of about 15,000 ft (4,572 m) (Buschbach and Kolata 1991; Goetz et al. 1992; McBride and Kolata 1999). The basin structure across the proposed CO_2 storage site is shown in two regional cross sections in Figure 2.3 and Figure 2.4.

The thickest part of the Cambrian Mount Simon Sandstone is in northeast Illinois, where it exceeds a thickness of 2,600 ft (792 m). A post-Cambrian shift in basin subsidence gradually caused the center of the basin to migrate southeast. As a result, today the deepest part of the Illinois Basin lies in extreme southeastern Illinois. In that area, the top of the Precambrian basement is deeper than 14,000 ft (4,267 m), and the depth to the Mount Simon Sandstone is about 13,500 ft (4,114 m) (Willman et al. 1975). In west-central Illinois the Precambrian basement dips gently to the east-southeast (Figure 2.5).

[1] http://www.isgs.uiuc.edu/
[2] http://www.usgs.gov/
[3] http://sequestration.org/

Figure 2.2. The Illinois Structural Basin Within the Midwestern United States (modified from Buschbach and Kolata 1991)

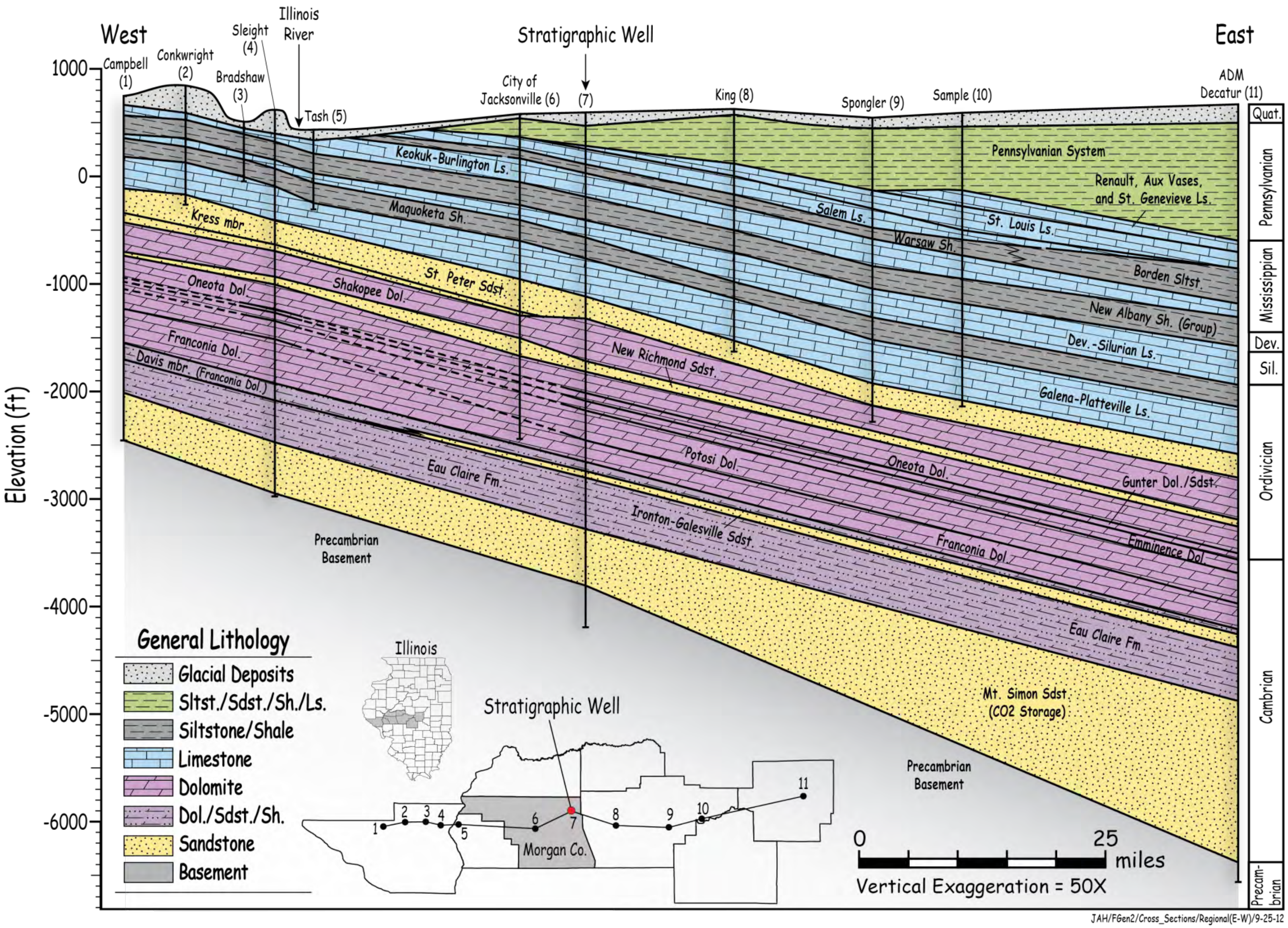

Figure 2.3. Regional East-West Cross Section Across the Western Half of Illinois (based in part on data from ISGS 2011)

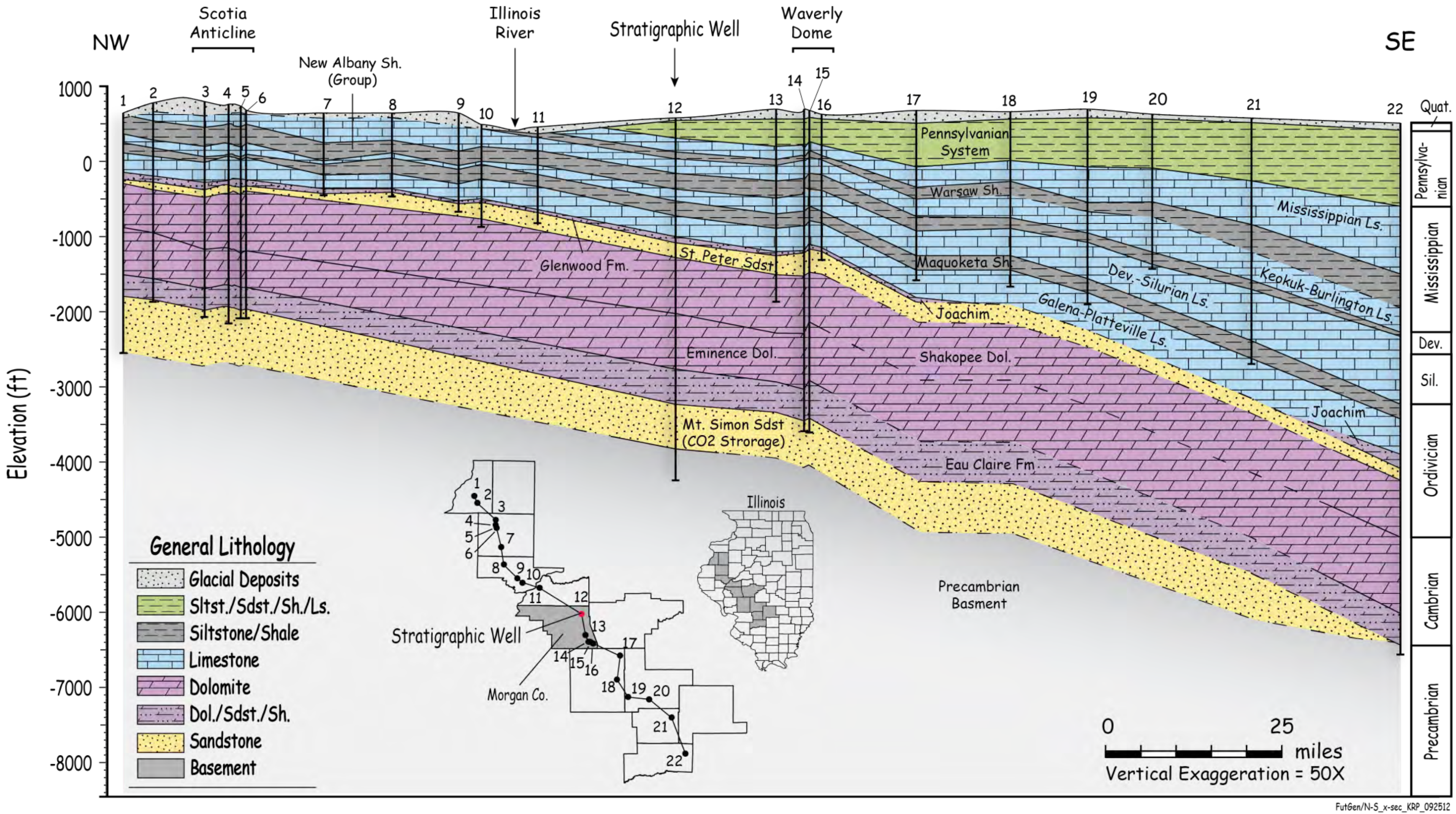

Figure 2.4. Regional North-South Cross Section (based in part on data from ISGS 2011a)

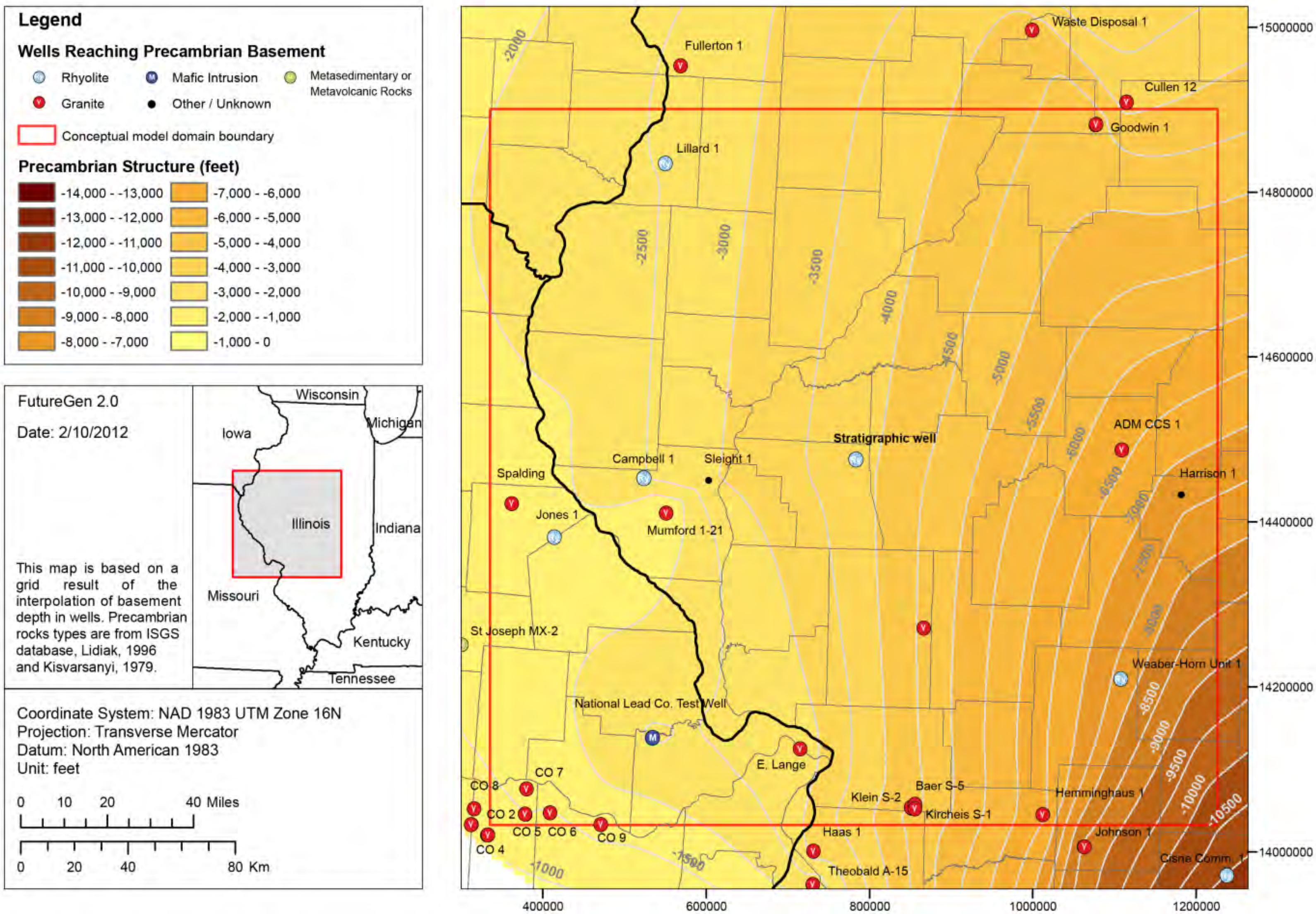

Figure 2.5. Structure and Lithology of the Precambrian Basement in Wells in Western Illinois and Portions of Iowa and Missouri. (Modified from Willman et al. 1975 with additional data from MDNR 2012; Precambrian lithology from Kisvarsanyi 1979 and Lidiak 1996.)

2.1.2 Major Stratigraphic Units

The following discussion includes the regional characteristics of the Precambrian basement that underlies the injection zone, the Mount Simon and Elmhurst sandstones (proposed CO_2 injection zone), the confining zone immediately above the injection zone (upper Eau Claire Formation), and the secondary confining zones.

2.1.2.1 Precambrian Basement

Regionally, the Precambrian basement (see Figure 2.5) that underlies the Mount Simon Sandstone includes silica-rich igneous and metamorphic rock (Bickford et al. 1986; McBride and Kolata 1999). Similar Precambrian rocks also underlie the Mount Simon Sandstone equivalent (the Lamotte Sandstone) in Missouri (Kisvarsanyi 1979; Lidiak 1996). Considerable topographic relief (up to 1,800 ft [549 m]) has been mapped on the Precambrian basement (Leetaru and McBride 2009). Much of this relief is erosional topography created prior to deposition of Cambrian sediments and may exert considerable influence on injection zone thickness, lithology (character of the rock formation), and lithofacies characteristics of the Mount Simon Sandstone (Bowen et al. 2011).

Published analyses of the Precambrian basement rocks regionally within the Illinois Basin indicate they have extremely low porosity and permeability (Table 2.1). Furthermore, wireline log calculations of permeability indicate that fractures in the Precambrian rock are not transmissive. Available data indicate that the basement rock represents a basal confining, no-flow boundary for proposed injection of CO_2 into the Mount Simon Sandstone.

Table 2.1. Published Physical Properties for Precambrian Basement Rocks in the Illinois Basin

Reference	Permeability (mD)	Porosity (%)	Pore Compressibility (Pa^{-1})	Hydraulic Conductivity (cm/sec)
EPA (2011)	0.0091			$1.8x10^{-12}$
Birkholzer et al. (2008)	0.03 in top portion	0.05 in top portion		
Birkholzer et al. (2008)	0.0001	0.05		
Zhou et al. (2010)		0.05		
Zhou et al. (2010)	Kh and Kv = $0.0001E^{-15}$ m^2	0.05	$7.42E^{-10}$ and $22.26E^{-10}$	
Sminchak (2011)	0.0008 (ave. of 13 samples)	1.8 (ave. of 13 samples)		

2.1.2.2 Geology of the Injection Zone: Mount Simon and Elmhurst Sandstones

The Mount Simon Sandstone along with the Elmhurst Sandstone member of the Eau Claire Formation is the target zone for the injection of CO_2. The Mount Simon Sandstone has a proven injection-zone capacity, based on a number of natural-gas storage facilities across the Illinois Basin (Buschbach and Bond 1974; Morse and Leetaru 2005) and data from the Archer Daniels Midland (ADM) carbon sequestration site in Macon County, Illinois (Leetaru et al. 2009).

More than 900 wells, mostly pre-1980, have been drilled into the Mount Simon Sandstone in the Illinois Basin (ISGS 2011a); about 50 of these wells in Illinois extend to the Precambrian basement underlying the Mount Simon. Most of the wells drilled into the Mount Simon Sandstone prior to 1980 lack well-log suites suitable for quantitative analysis of porosity and permeability. In north-central

Illinois where the Mount Simon Sandstone is used for natural-gas storage, some detailed analyses of porosity, permeability, and lithofacies connectivity are available, although most gas-storage wells only penetrate the upper part of the Mount Simon (Morse and Leetaru 2005).

The regional structural dip of the Mount Simon Sandstone in Morgan County is to the southeast as shown in Figure 2.6. The thickness of the Mount Simon ranges from less than 500 ft (152 m) in westernmost and southwestern Illinois to more than 2,500 ft (792 m) in the northeastern part of the state (Figure 2.7). The Mount Simon Sandstone thins or is not present over Precambrian structures and paleotopographic highs, such as the Ozark Dome in southeastern Missouri, and localized highs several tens of miles west and south of the proposed Morgan County CO_2 storage site (Figure 2.6 and Figure 2.9).

Regionally, the Mount Simon Sandstone varies in lithology from conglomerate to sandstone to shale. Bowen et al. (2011) recognized six dominant lithofacies in studying the Mount Simon Sandstone from 135 wells over a multi-state area (eastern Illinois, Indiana, northern Kentucky, and Tennessee). These lithofacies include cobble conglomerate, stratified gravel conglomerate, poorly sorted sandstone, well-sorted sandstone, interstratified sandstone and shale, and shale. Diagenetic clay minerals in the Mount Simon Sandstone most commonly include illite and kaolinite. Cements that can occlude porosity include iron oxide, authigenic clay, and quartz overgrowths (Bowen et al. 2011).

The ADM UIC Class 6 Application (EPA 2011) reported that in the ADM carbon capture and storage (CCS) well number 1 (ADM CCS#1 well), poorly sorted sandstone lithofacies, containing intervals of better-sorted finer and coarser sandstone, were the most common lithofacies in the Mount Simon Formation; some thin shale stringers were also present. An arkosic interval was selected as the injection target. The ADM CCS#1 well is closer to the center of the Cambrian Illinois Basin depocenter than is the proposed Morgan County CO_2 storage site. Lithologic variability is expected across the basin, especially in the lower part of the Mount Simon Sandstone, where lithologies can change due to paleotopography and depositional environment.

The Mount Simon Sandstone represents continental and shallow marine environments of deposition that reflect gentle basin subsidence and gradual transgressive marine encroachment over the deeply eroded Precambrian basement rocks (Leetaru et al. 2009). Terrestrial depositional environments such as alluvial fans, braided streams, eolian dunes, and wadi deposits are interpreted in the Mount Simon core from wells and outcrop in Missouri and Wisconsin (Houseknecht 2001; Hunt 2004; Wilkens et al. 2011). Transitional marine depositional environments represented in the Mount Simon Sandstone include barrier islands, deltas, and tidal inlets with shallow marine sands and coastal bars (Sargent and Lasemi 1993; Wilkens et al. 2011; Driese et al. 1981). The continental depositional lithofacies transition upward into marine facies of the Eau Claire Formation. This change is indicative (along with patterns of sediment thickening) of basin subsidence and sea-level rise during a major marine transgressive event (Kolata and Nimz 2010).

Included as part of the proposed injection zone is the Elmhurst Sandstone, the basal (lowest) member of the Eau Claire Formation (see Figure 2.1). The Elmhurst Sandstone consists of fine- to medium-grained, fossil-bearing, white, red, or gray sandstones with irregular interbedded gray shales and minor dolomite (Willman et al. 1975). Regionally, these sandstones are porous, permeable, and in hydrologic communication with the Mount Simon Sandstone (Buschbach and Bond 1974; Hanson 1960; Hunt 2004; Morse and Leetaru 2005).

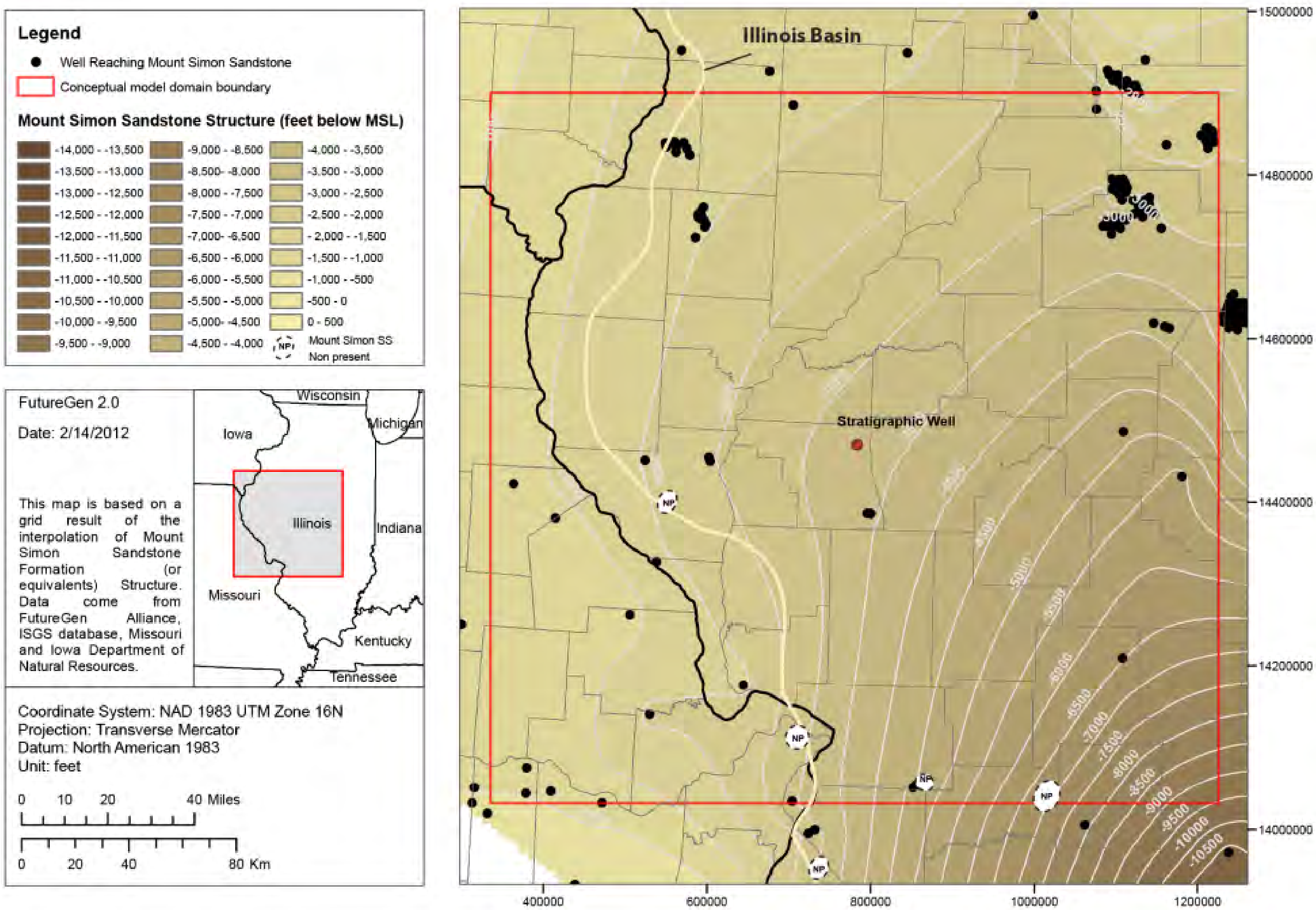

Figure 2.6. Structure on Top of the Mount Simon Sandstone in West-Central Illinois and Portions of Iowa and Missouri (based in part on data from ISGS 2011a, MDNR 2012, and IDNR 2012). White areas represent nondeposition of the Mount Simon Sandstone on Precambrian paleotopographic highs.

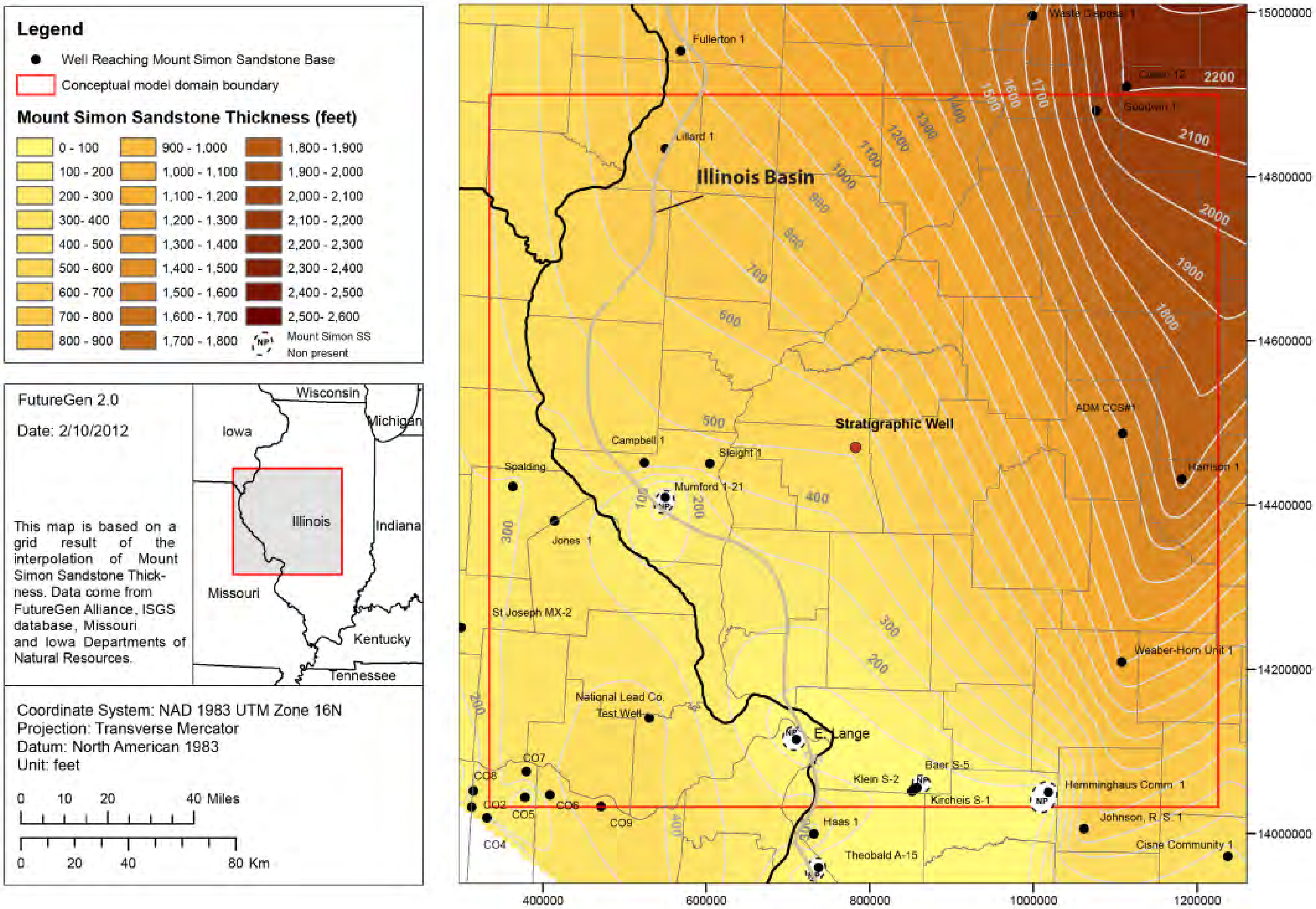

Figure 2.7. Thickness of the Mount Simon Sandstone in West-Central Illinois and Portions of Iowa and Missouri. The Mount Simon is thin or absent across localized Precambrian highs west and south of Morgan County. (Based in part on data from ISGS 2011a, MDNR 2012, and IDNR 2012)

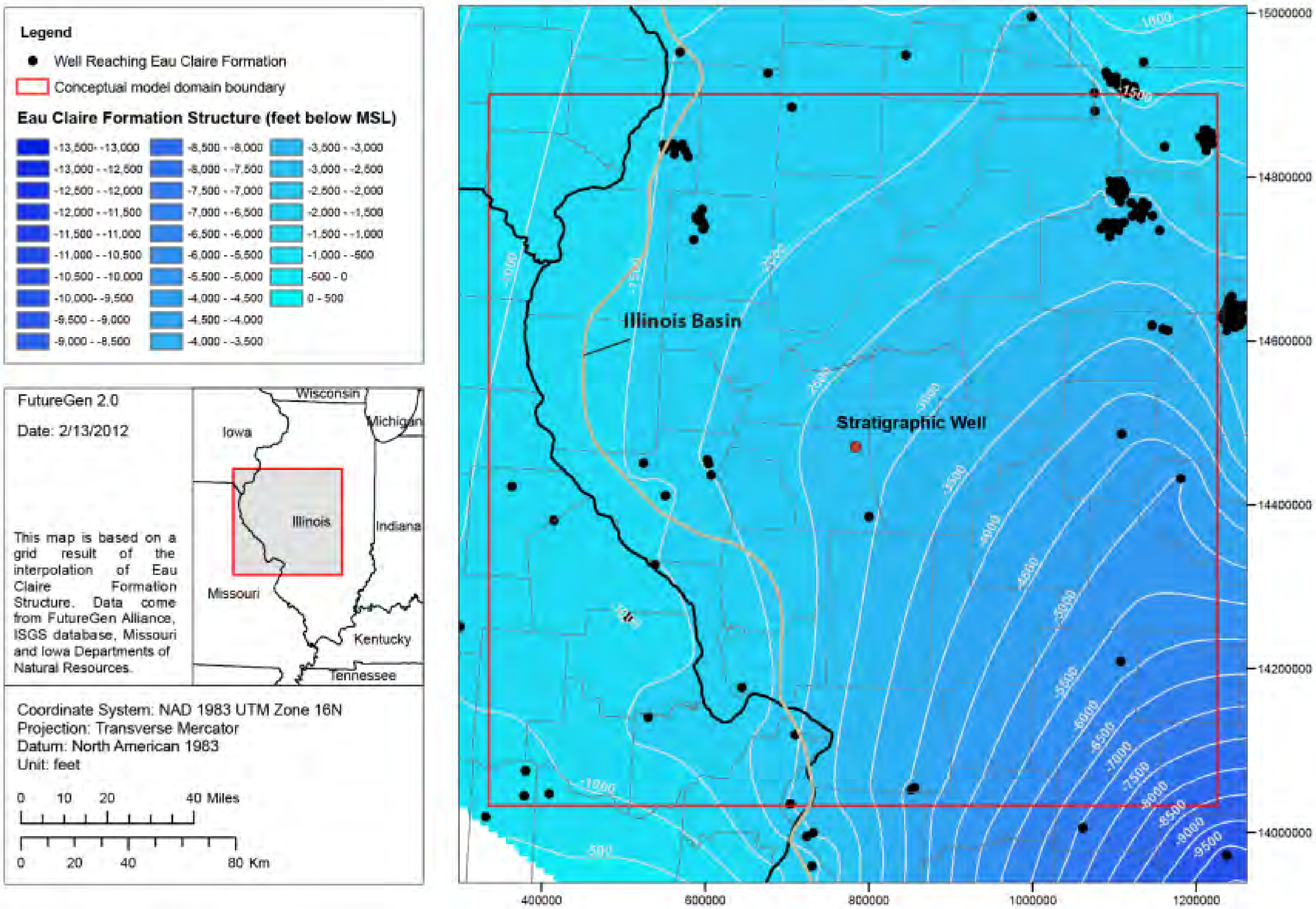

Figure 2.8. Structure-Contour Map for the Top of the Eau Claire Formation in West-Central Illinois and Portions of Iowa and Missouri (based in part on data from ISGS 2011a, MDNR 2012, and IDNR 2012)

2.1.2.3 Geology of the Confining Zone: Eau Claire Formation

The Eau Claire Formation is a widespread, heterolithic carbonate and fine siliciclastic unit present across west-central Illinois (Figure 2.8) and parts of seven adjoining states (Sminchak 2011). The low-permeability Lombard and Proviso members of the Eau Claire form an effective confining layer at 38 natural-gas storage reservoirs in Illinois (Buschbach and Bond 1974; Morse and Leetaru 2005). The confining members of Eau Claire overlie the Elmurst Sandstone member (see Figure 2.1).

Regionally, the Lombard member of the Eau Claire Formation consists of glauconitic and sandy dolomite interbedded with mudstones and shale; the shale content increases to the south and sand content increases to the west and north (Willman et al. 1975). The Lombard member is overlain by the Proviso member, which is characterized by limestone, dolomite, sandy siltstone, and shale beds. The Lombard and Proviso members are continuous and extend across several buried Precambrian highs in the region.

In addition to the Eau Claire Formation, the widespread, low-permeability Franconia Dolomite Formation (Figure 2.1) (Kolata and Nimz 2010) may be considered a secondary confining zone for the containment of scCO_2 within the region (see Figure 2.1).

2.1.3 Site Geology

The proposed storage site is located approximately 11 mi (18 km) northeast of the City of Jacksonville, 6 mi (9.7 km) north of the unincorporated village of Alexander, and 6 mi (9.7 km) southwest of Ashland (see Figure 2.2). To support the evaluation of the Morgan County site as a potential carbon storage site a deep stratigraphic well (Figure 2.9) was drilled and extensively characterized. The stratigraphic well, located at longitude 90.0528W, latitude 39.8067N, is approximately 1 mi (1.6 km) east of the planned storage site. The results and interpretations of the data from the stratigraphic well are presented in this supporting documentation and used to support the following discussions of site-specific geology and hydrology at the proposed Morgan County CO_2 storage site.

The stratigraphic well reached a total depth of 4,826 ft (1,471 m) bgs within the Precambrian basement. The well penetrated 479 ft (146 m) of the Eau Claire Formation and 512 ft (156 m) of the Mount Simon Sandstone. Contact picks in the stratigraphic well (Figure 2.9) are based on correlations with wells in the ISGS database as well as comparison of the well cuttings with lithologies in drillers logs and published descriptions.

The stratigraphic well was extensively characterized, sampled, and geophysically logged during drilling. These resulting data, together with the regional data, form the basis for developing a conceptual model. Intervals where wireline geophysical logs and rotary side-wall drill cores were acquired are listed in Table 2.2. A total of 177 ft of whole core were collected from the lower Eau Claire-upper Mount Simon Sandstone (Table 2.3) and 34 ft were collected from lower Mount Simon Sandstone-Precambrian basement interval. In addition to whole drill core, a total of 130 side-wall core plugs were obtained from the combined interval of the Eau Claire Formation, Mount Simon Sandstone, and the Precambrian basement. Depths for the primary hydrogeologic units relevant to injection of CO_2 and protection of USDWs are listed in Table 2.4. Slabbed cores from the Lombard and Elmhurst members and the Mount Simon Sandstone are shown in Figure 2.10.

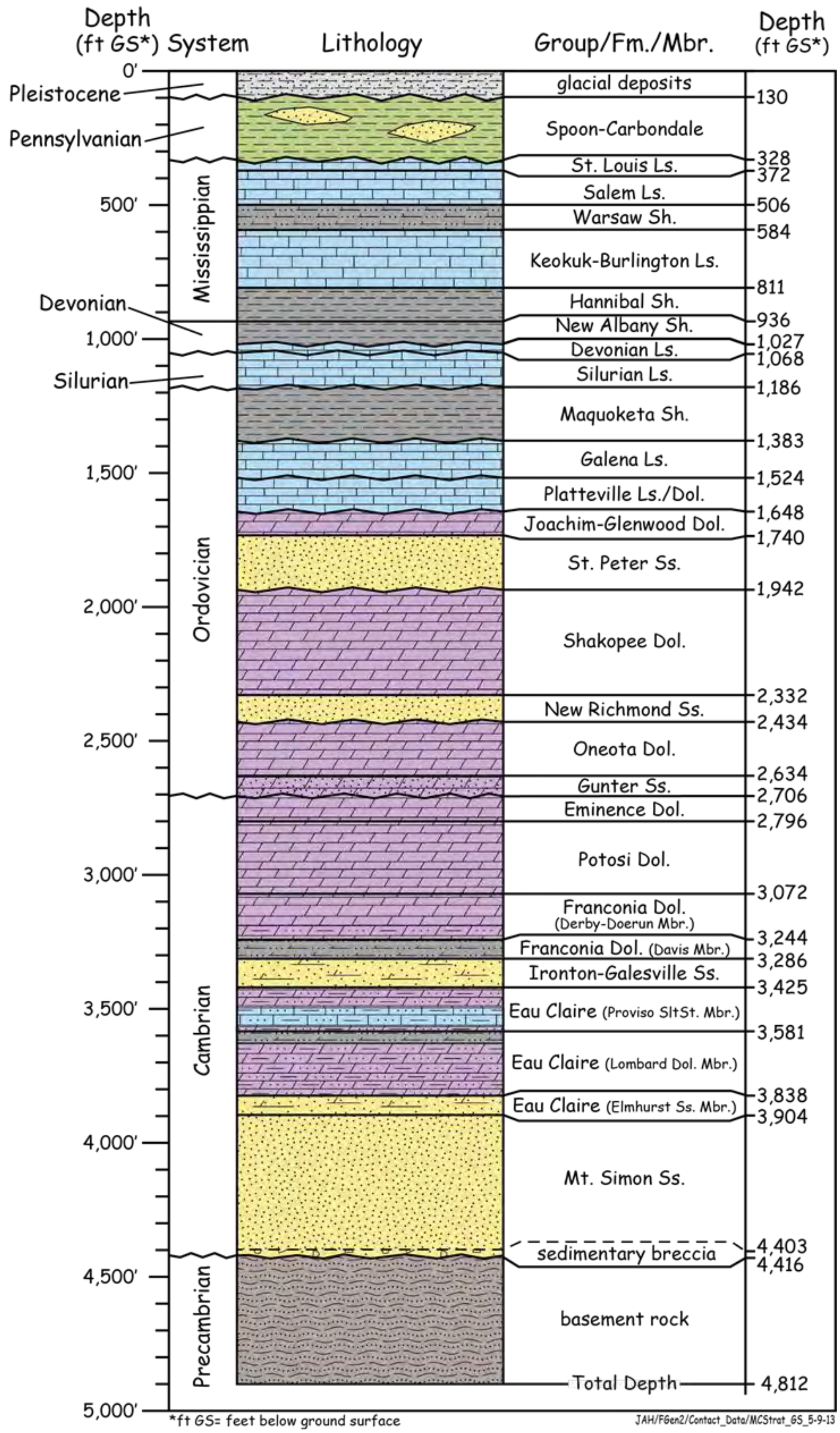

Figure 2.9. Stratigraphic Column for the Recently Drilled Stratigraphic Well at the Proposed Morgan County CO_2 Storage Site. Wavy lines represent major unconformities reported for the Morgan County area by Willman et al. (1975).

Table 2.2. Intervals of Geophysical Wireline Characterization Logs and Side-Wall Cores Collected in the Stratigraphic Well

Log Type	Run #	Log Interval Top (ft bgs)	Log Interval Bottom (ft bgs)
Triple Combo	1	31	2,036
Resistivity	1	31	2,036
Triple Combo (Gamma, Neutron, Density) plus Photoelectric Cross-Section Log	2	553	4,015
Sonic Dipole	2	566	3,962
Resistivity Image	2	564	4,013
Spectral Gamma Ray	2	372	3,978
Elemental Capture Log	2	91	4,014
Rotary Side-Wall Cores	2	Top Sample 684	Bottom Sample 3,968
Triple Combo (Gamma, Neutron, Density) plus Photoelectric Cross-Section Log	3	3,932	4,806
Sonic Dipole	3	3,932	4,806
Resistivity Image	3	3,966	4,810
Ultrasonic Image	3	3,922	4,886
Spectral Gamma Ray	3	3,932	4,806
Elemental Capture Log	3	81	4,024
Nuclear Magnetic Resonance	3	3,932	4,806
Rotary Side-Wall Cores	3	Top Sample 4,020	Bottom Sample 4,782

Table 2.3. Whole-Core Intervals Collected from the Stratigraphic Well

Core Run #	Core Diameter (in.)	Interval Top (ft bgs)	Interval Bottom (ft bgs)	Number of Feet Cored/ Recovered	Stratigraphic Unit
1	3.5	3,758	3,868	110/107.8	Eau Claire Lombard and Elmhurst members
2	3.5	3,868	3,908	40/30.0	Eau Claire Elmhurst member
3	3.5	3,910	3,943	33/33.0	Upper Mount Simon Sandstone
4	4.5	4,486	4,420	34/25.9	Lower Mount Simon Sandstone and Precambrian basement
5	4.5	4,420	4,428	8/8.5	Precambrian basement

Table 2.4. Hydrogeology of the Injection and Confining Zones Within the Stratigraphic Well

Stratigraphic Unit	Hydrostratigraphic Unit	Top Depth (ft bgs)	Thickness (ft)
Eau Claire (Proviso member)	Eau Claire Siltstone (Confining zone)	3,425	156
Eau Claire (Lombard member)	Eau Claire Dolomite (Confining zone)	3,581	257
Eau Claire (Elmhurst member)	Eau Claire Sandstone (Injection zone)	3,838	66
Mount Simon Sandstone	Mount Simon Sandstone (Injection zone)	3,904	512
Precambrian basement	(Lower No-Flow Boundary)	4,416	>400

Figure 2.10. Slabbed Whole Core from the Lowermost Lombard Member Mudstones and Siltstones, the Elmhurst Sandstones, and the Lower Mount Simon Sandstones from the Stratigraphic Well

2.1.3.1 Injection Zone

The combined thickness of the proposed injection zone, which includes the Mount Simon and Elmhurst sandstones, is 565 ft (172 m) at the stratigraphic well (Figure 2.9). As observed in cuttings, core logs, and image logs, the Mount Simon Sandstone primarily consists of fine-to-coarse quartz arenite with local granule-rich quartz or arkosic sandstone beds. Based on the computed mineralogy (Elemental Analysis [ELAN]) log, feldspar appears to be considerably more common in the lower part of the Mount Simon Sandstone. In Figure 2.11, cored intervals are indicated with red bars; rotary side-wall core and core-plug locations are indicated to the left of the lithology panel. Standard gamma ray and resistivity curves are shown in the second panel; ELAN-calculated permeability (red curve) is in the third panel, along with two different lab measurements of permeability for each rotary side-wall core. Neutron- and density-crossplot porosity is shown in the fourth panel, along with lab-measured porosity for core plugs and rotary side-wall cores. The proposed injection interval (location of the horizontal wells' injection laterals) is highlighted on the geophysical log panels in Figure 2.11.

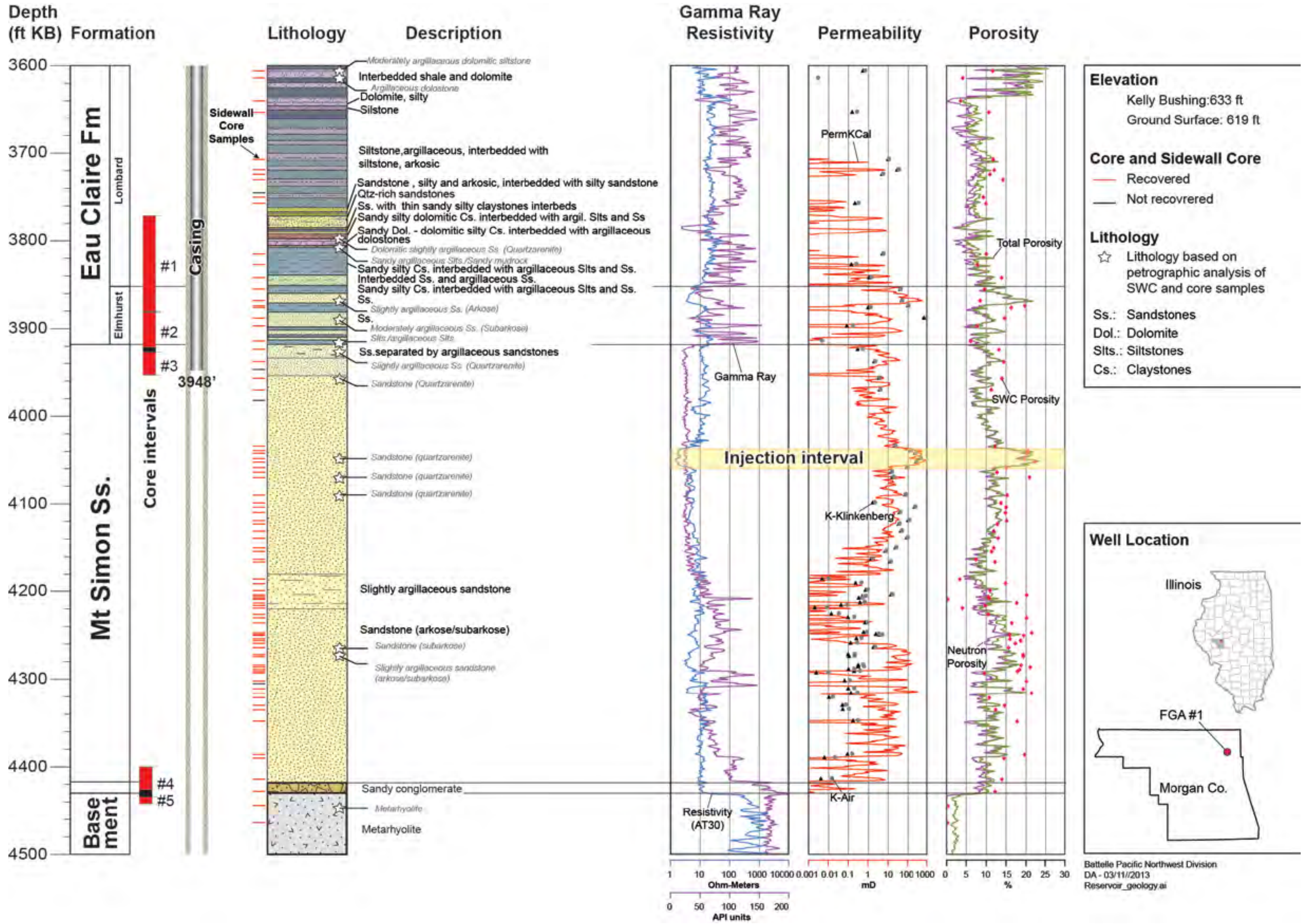

Figure 2.11. Lithology, Mineralogy, and Hydrologic Units of the Proposed Injection Zone (Mt Simon and Elmhurst) and Lower Primary Confining Zone (Lombard), as Encountered Within the Stratigraphic Well. Data are explained in the text.

Permeability in the sandstones, as measured in rotary side-wall cores and plugs from whole core, appears to be dominantly related to grain size and abundance of clay. Horizontal permeability (Kh) data in the stratigraphic well outnumber vertical permeability (Kv) data, because Kh could not be determined from rotary side-wall cores. However, Kv/Kh ratios were successfully determined for 20 vertical/horizontal siliciclastic core-plug pairs cut from intervals of whole core. Within the Mount Simon Sandstone, the horizontal permeabilities of the lower Mount Simon alluvial fan lithofacies range from 0.005 to 0.006 mD and average ratios of vertical to horizontal permeabilities range from 0.635 to 0.722 (at the 4,318−4,388 ft KB depth, Figure 2.11). Horizontal core-plug permeabilities range from 0.032 to 2.34 mD at the 3,852−3,918 ft KB depth; Kv/Kh ratios for these same samples range from 0.081 to 0.833. Details of Kh and Kv by depth and by numerical model layer are covered in Chapter 3.0.

2.1.3.2 Confining Zone

The Proviso and Lombard members of the Eau Claire Formation form the primary confining zone for the proposed Morgan County CO_2 storage site. The combined thickness of these strata is 413 ft (126 m) at the stratigraphic well. Eighty ft (24 m) of whole core were obtained in the Lombard member of the Eau Claire Formation, along with 13 rotary side-wall cores. In addition, 10 rotary side-wall cores were collected in the Proviso member.

Rock cuttings and rotary side-wall core lithologies from the upper Proviso member include tan to light brown, dense, occasionally glauconitic microcrystalline, slightly dolomitic limestone. The lower half of the Proviso member is a tan to cream, argillaceous, and slightly silty microcrystalline dolomite with interbedded siliceous cemented quartz sandstone. The sand grains are very fine- to fine-grained, sub-rounded and clear to white with occasional glauconite.

Thinly bedded to laminated siltstone and mudstone dominate lithologies in the Lombard; whole core and rotary side-wall cores indicate lithologies are extremely heterolithic. Well cuttings include red to light brown, non-calcareous shale near the top of the member with tan to light brown, siliceous, finely crystalline dolomite. Thin bands of dolomite are present in some rotary side-wall cores. Minor abundances of glauconite are present in drill cuttings throughout the section; and trace amounts of oolites were observed in cuttings near the top of the unit. Thin beds of quartz sandstone are present in the Lombard, immediately overlying the Elmhurst member.

Wireline and core-based lithology, porosity, and permeability for the primary confining zone are shown in Figure 2.12. The computed lithology track indicates the upward decrease in quartz silt and increase in carbonate in the Proviso member, along with a decrease in permeability. The permeabilities of the rotary side-wall cores in the Proviso range from 0.000005 mD to 1 mD (Table 2.5); the one sample lower than 0.0001 is not shown in Figure 2.12. Permeabilities in the Lombard member range from 0.001 mD to 28 mD, reflecting the greater abundance of siltstone in this interval, particularly in the lowermost part of the member. The upward decrease in computed log permeability (red curve in the permeability panel) reflects decreasing silt supply and possibly increasing water depths of the original depositional environment.

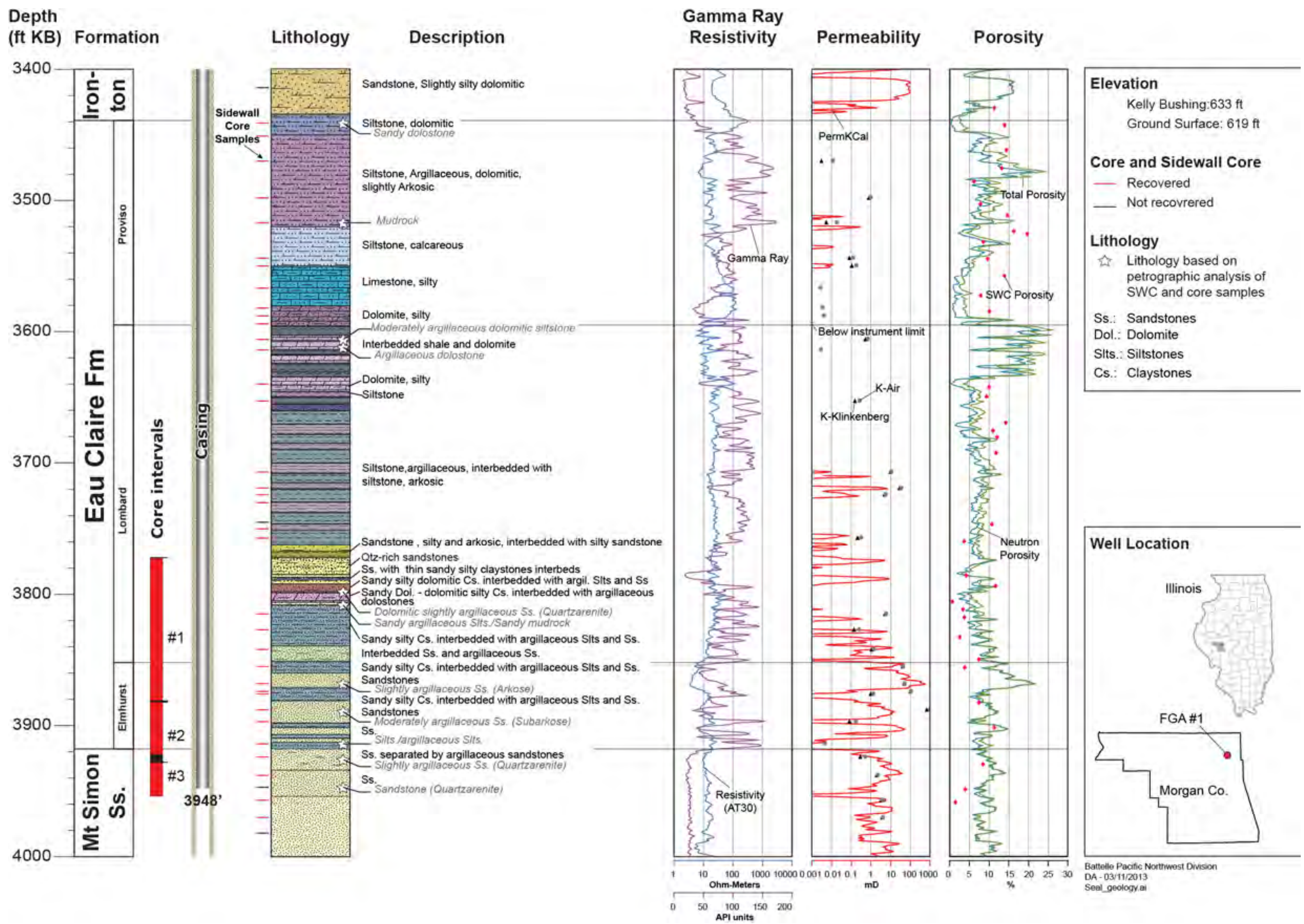

Figure 2.12. Relationship Between Lithology, Mineralogy, Side-Wall Core and Wireline Log Computed (ELAN) Permeability for the Eau Claire Formation and Uppermost Mount Simon Intervals in the Stratigraphic Well. One Proviso sample with permeability below 0.0001 mD is not shown.

Whole core plugs and associated vertical permeabilities are available only from the lowermost part of the Lombard. Thin (few inches/centimeters), high-permeability sandstone streaks resemble the underlying Elmhurst; low-permeability siltstone and mudstone lithofacies have vertical permeabilities of 0.0004-0.465 mD, and Kv/Kh ratios of 0.000 to 0.17.

Table 2.5. Permeabilities from Proviso Member Rotary Side-Wall Cores

Formation	Depth (ft bgs)	Horizontal Permeability (mD)
Eau Claire (Proviso member)	3,427	.0001
Eau Claire (Proviso member)	3,437	.0001
Eau Claire (Proviso member)	3,456	.003
Eau Claire (Proviso member)	3,484	.795
Eau Claire (Proviso member)	3,503	.005
Eau Claire (Proviso member)	3,530	.082
Formation	Depth (ft bgs)	Horizontal Permeability (mD)
Eau Claire (Proviso member)	3,536	.108
Eau Claire (Proviso member)	3,553	.0005
Eau Claire (Proviso member)	3,568	.001
Eau Claire (Proviso member)	3,574	.001
Eau Claire (Proviso member)	3,580	.000005

It is important to note that regional well-log correlations and drilling data indicate that the Lombard and Proviso members of the Eau Claire Formation do not pinch out against paleotopographic highs west of the proposed Morgan County CO_2 storage site. Instead, these confining units are laterally continuous and overstep the Precambrian highs in Pike County.

2.1.3.3 Secondary Confining Zone

The combined 244-ft (74-m) interval of the Franconia Dolomite Formation (Figure 2.9) form a secondary confining zone for the Mount Simon and Elmhurst injection zones. The Franconia lithology, as observed in well cuttings, is dominated by tan to light brown, microcrystalline dolomite. Dolomite in cuttings from the upper part of the Franconia contains minor amounts of fine-grained, clear and sub-rounded quartz sand. The lower part of the Franconia is a slightly pyritic and glauconitic cream to light brown, microcrystalline dolomite with scattered grains of clear, sub-rounded quartz sand.

The underlying Davis member is a low-permeability, light gray to light brown, microcrystalline dolomite and argillaceous (shaley), sandy dolomite. The lowermost part of the unit is a tight argillaceous, dolomitic sandstone that marks the upward transition from the Ironton Sandstone. The Davis member dolomites regionally grade laterally into low-permeability shales (Willman et al. 1975).

The ELAN geophysical logs indicate effective porosities (total porosity minus shale effect or clay-bound water) in the Franconia range from <0.01 to 7 percent, with an average of 3 percent; and effective porosities in the Davis interval range from <0.01 to 3 percent, with an average of 0.1 percent in the upper part of the Davis, and an average effective porosity of 0.79 percent in the lower, more argillaceous (clay-rich) part of the unit.

The ELAN geophysical logs indicated permeabilities are generally less than the wireline tool limit of 0.01 mD throughout the secondary confining zone. Two rotary side-wall cores were taken from the

Franconia, and three side-wall cores were cut in the Davis member. Laboratory-measured rotary side-wall core (horizontal) permeabilities (Table 2.6) are very low (0.001−0.000005 mD). The permeabilities of the two Franconia samples were measured with a special pulse decay permeameter; the sample from 3,140 ft bgs (957 m) has a permeability less than the lower instrument limit of 0.000005 mD. A relatively high porosity (7.8 percent porosity with 12.5-mD permeability) was recorded for one Davis side-wall core. This appears to represent an isolated thin (less than 1 ft [15 cm] sand stringer within the lower Davis member).

Table 2.6. Rotary Side-Wall Core Permeabilities from the Secondary Confining Zone

Formation	Depth (ft bgs)	Horizontal Permeability (mD)
Franconia Dolomite	3,140	<.000005
Franconia Dolomite	3,226	.000006
Davis	3,268	.001
Davis	3,291	0.125
Davis	3,303	12.5

Vertical core plugs are required for directly determining vertical permeability and there are no data from the stratigraphic well for vertical permeability or for determining vertical permeability anisotropy in the secondary confining zone. However, Kv/Kh ratios of 0.007 have been reported elsewhere for Paleozoic carbonate mudstones (Saller et al. 2004).

2.2 Injection Zone Water Chemistry

Analyses of two formation fluid samples from the stratigraphic well, collected at a depth of 4,048 ft (1,234 m) below the kelly bushing (bkb) (Sample 11) using Schlumberger's Modular Formation Dynamics Tester (MDT) sampler, are shown in Table 2.16. Based on these initial samples, the best estimate total dissolved solids (TDS) concentration selected for initial simulation is a constant 47,500 mg/L throughout the Mount Simon Sandstone. The EPA (2011) reported TDS for eight samples from the Mount Simon Sandstone from the CCS#1 near Decatur, Illinois (Table 2.7). TDS varied with depth yielding a minimum concentration of 164,500 mg/L at 5,772 ft (1,759 m) and a maximum concentration of 228,100 mg/L at 7,045 ft (2,147 m). Note that these depths are 2,000 to 3,000 ft (610 to 914 m) deeper than those encountered at the Morgan County CO_2 storage site and would represent an upper maximum for TDS at the proposed storage site.

Table 2.7. Data from Fluid Samples Collected with the MDT Sampler from the Mount Simon Sandstone in the CCS#1 Well at the Decatur Site (modified after EPA 2011)

Sample ID	Depth (ft)	Formation Pressure (psi)	Formation Temperature (degrees F)	TDS (mg/L)	Brine Density (g/L)
MDT-4	5,772	2,582.9	119.8	164,500	1.09
MDT-3	6,764	3,077.5	125.1	185,600	1.12
MDT-14	6,764	3,077.5	125.1	179,800	Not analyzed
MDT-5	6,840	3,105.9	125.0	182,300	1.12
MDT-9	6,840	3,105.9	125.0	219,800	Not analyzed
MDT-2	6,912	3,141.8	125.8	211,700	1.14
MDT-1	7,045	3,206.1	125.7	228,100	1.12
MDT-8	7,045	3,206.1	125.7	201,500	Not analyzed

2.3 Geologic Structure

Known major geologic structures in Illinois are shown in Figure 2.13. The proposed storage site is on the southern flank of the very broad Sangamon Arch. Structural dips on sedimentary strata within the western part of the Illinois Basin are low—generally less than one degree to the east and southeast, based on regional structure maps (Figure 2.6 and Figure 2.8).

2.3.1 Site Geologic Structure

The geologic structure in the vicinity of the proposed Morgan County CO_2 storage site consists of a very gentle, 0.25-degree dip to the southeast, as determined by the three-dimensional (3D) geologic conceptual model developed for the site that used local and regional well data. Low structural dips are confirmed by the resistivity-based image logs (Formation Microimager) acquired in the stratigraphic well. The principal geologic structure in proximity to Morgan County is the very broad Sangamon Arch (Figure 2.13). Neither this map nor any other published sources (Whiting and Stevenson 1965; Kolata and Nelson 1991) indicate the existence of any mapped faults or fracture zones in the vicinity of the proposed Morgan County CO_2 storage site.

2.3.1.1 Reflection Seismic Profiles

Two two-dimensional (2D) surface seismic lines, shown in Figure 2.14, were acquired in January 2011 along public roads near the proposed Morgan County CO_2 storage site. A seismic survey gives an image of the subsurface based on differences in density and seismic wave velocity of the different geologic layers. It allows one to identify formation depths and thicknesses in addition to discontinuities such as faulting.

Both profiles indicate a thick sequence of Paleozoic-aged rocks. The seismic lines are not of optimal quality due to seismic noise,[1] but they do not indicate the presence of obvious faults or large changes in thickness of the injection or confining zones. Apparent discontinuities in the seismic lines appear to be an artifact of processing lines that were acquired along bends in roads as a straight line.

The seismic data acquired along these two seismic profiles were reprocessed by Exploration Development, Inc. in August 2012 to reduce the noise and improve the interpretation (Figure 2.15 and Figure 2.16). Both profiles indicate a thick sequence of Paleozoic-aged rocks with a contact between Precambrian and Mount Simon at 640 ms and a contact between Eau Claire and Mount Simon at 580 ms. Some vertical disruptions, which extend far below the sedimentary basin, remain and their regular spatial periodicity is unlikely related to faults. These discontinuous reflections could also be discontinuities created by collapse features associated with karsts formations that are known to occur in the Potosi Formation.

[1] Jaqucki P, V Smith, H Leetaru, and M Coueslan. 2011. *Seismic Survey Results and Interpretation – Illinois FutureGen 2.0 Potential Sites*. Schlumberger Carbon Services, Westerville, Ohio. Unpublished report to the FutureGen Industrial Alliance.

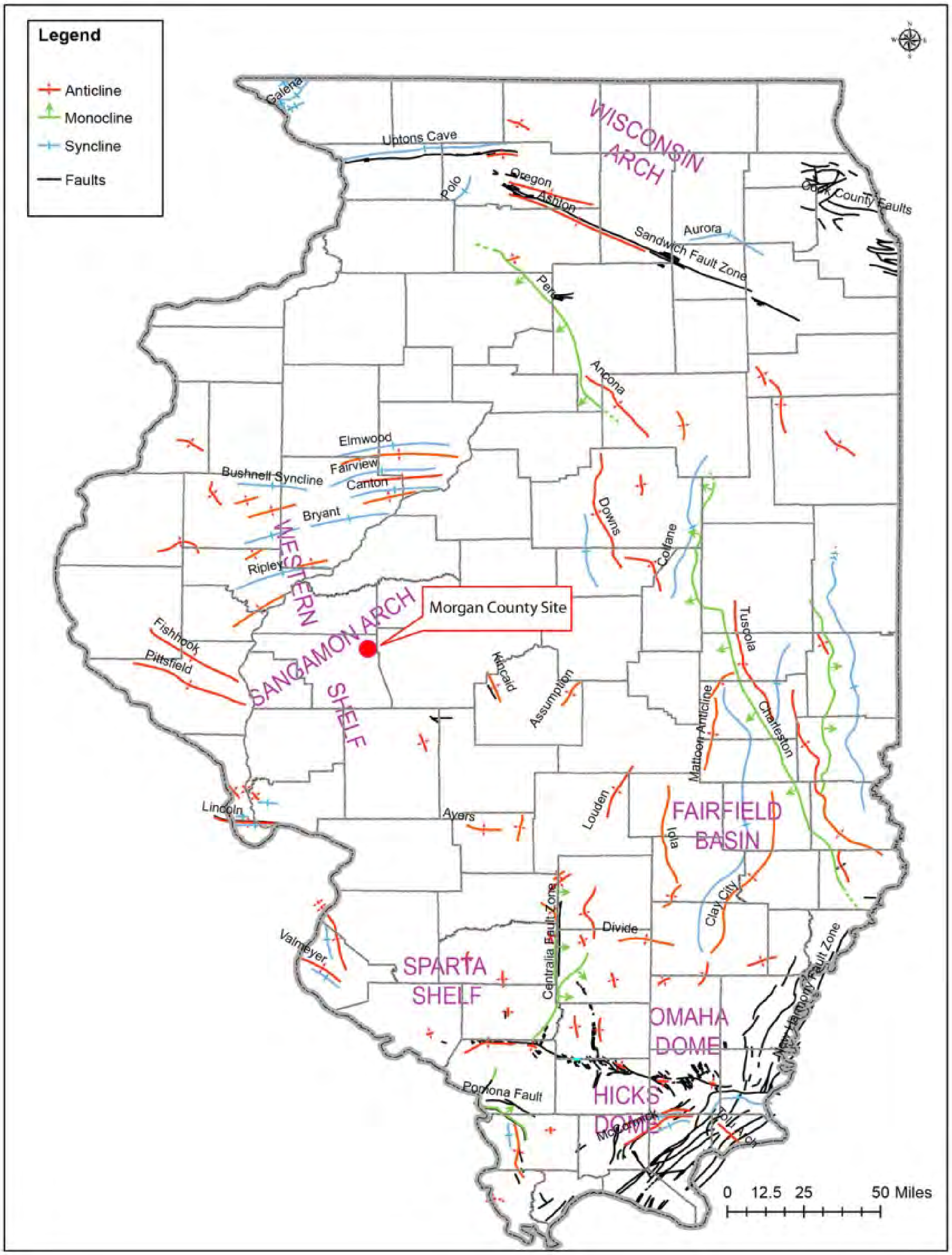

Figure 2.13. Structural Features of Illinois (modified from Nelson 1995)

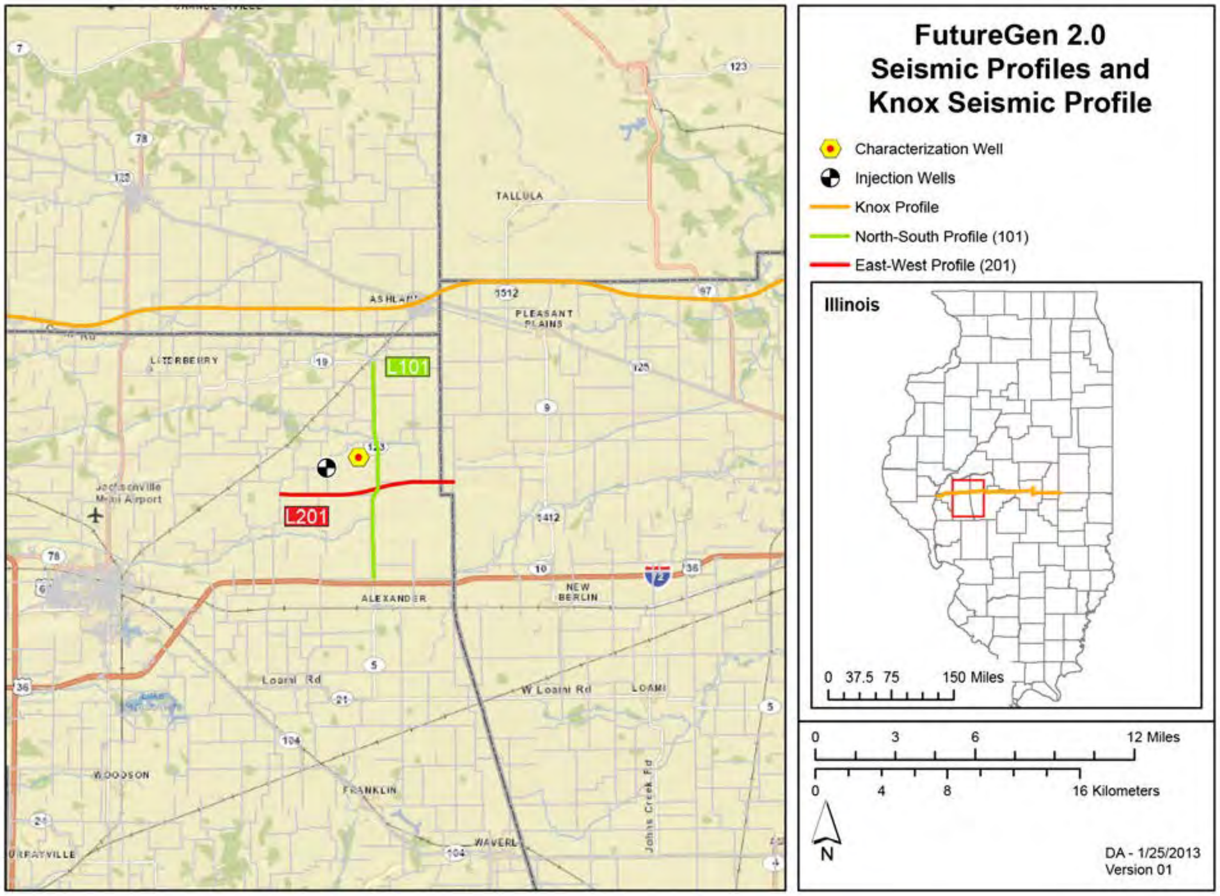

Figure 2.14. Location of the two 2D seismic survey lines, L101 and L201, at the proposed Morgan County CO_2 storage site. The north-south line is along Illinois State Highway 123. The Knox seismic profile completed in 2012 by the ISGS and that passes within 10 miles of the site is also drawn in orange.

A fault can usually be recognized and interpreted in seismic data if it creates a quasi-vertical displacement of 20 ms or more in several successive reflection events. This 20-ms reflector displacement rule represents a reflector discontinuity that most interpreters can see by visual inspection of seismic data. The amount of vertical fault throw that would produce a 20-ms vertical displacement would be (0.01 sec) X (P-wave interval velocity), for whatever interval velocity is appropriate local to a suspected fault. For the interval from the surface down to the Eau Claire at the FutureGen site in Morgan County, the P-wave interval velocity local to seismic lines L101 and L201 ranges from approximately 7,000 ft/s (shallow) to approximately 12,000 ft/s (deep). Thus, faults having vertical throws of 120 ft at the Eau Claire, and perhaps as little as 70 ft at shallow depths, should be detected if they traverse either profile. No faults with a clear vertical displacement have been identified; the only clear observation that can be made is the existence of a growth fault that affects Mount Simon and Eau Claire formations in the eastern part of the L201 profile at offset 28,000 ft (Figure 2.15). This growth fault is more than 1.5 miles away from the outermost edge of the CO_2 plume and does not extend far upward in the overburden. For these reasons, it is highly unlikely that it could affect the integrity of the reservoir.

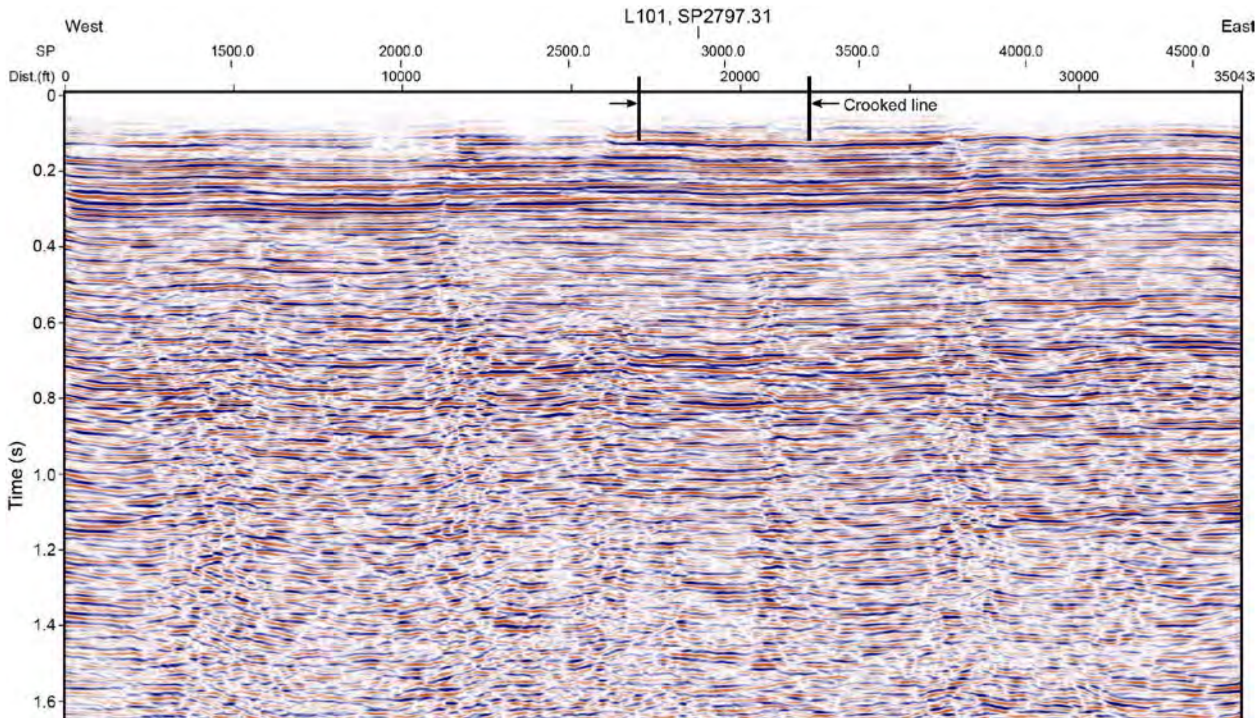

Figure 2.15. Reprocessed West-East 2D Seismic Line L201. Distance along horizontal axis is in feet and time (two-way travel time) along vertical axis is in seconds.

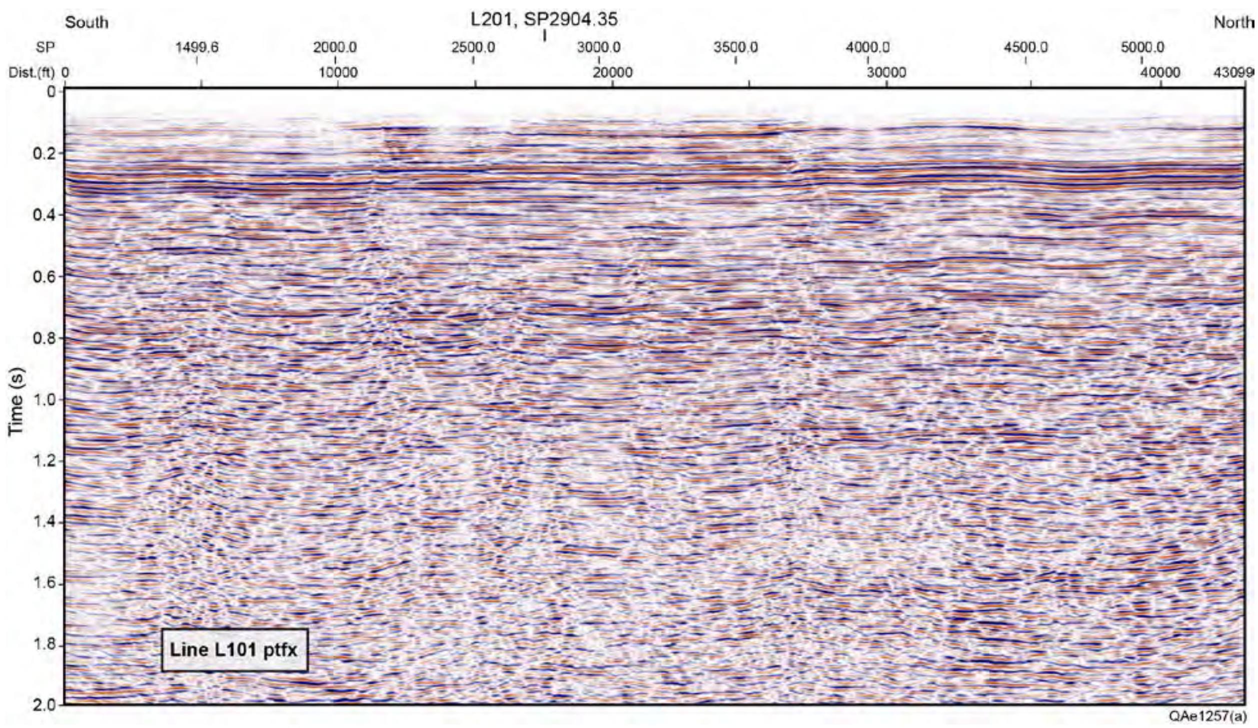

Figure 2.16. Reprocessed South-North 2D Seismic Line L101. Distance along horizontal axis is in feet and time (two-way travel time) along vertical axis is in seconds.

The Illinois State Geological Survey (ISGS) recently acquired a new 120-mi long seismic reflection survey across central Illinois as part of a DOE-sponsored research project to characterize reservoir rocks for geologic storage of carbon dioxide. The continuous east-west line extends from Meredosia to southwestern Champaign County (Figure 2.14). This line, which is currently under re-processing, will supply additional information about the structure of the sedimentary layers which will be correlated to the observations made on both profiles L101 and L201.

Future efforts at Morgan County will also include the acquisition of vertical seismic profiling data in the stratigraphic well to better evaluate the cause of the vertical disruptions in seismic reflections observed on the two existing seismic profiles.

2.3.1.2 Gravity Data

A site-specific surface gravity survey was conducted in November 2011, including 240 regularly spaced stations within a 2-mi by 2-mi area that covers the stratigraphic well site and the proposed storage site (Figure 2.17 and Figure 2.18). This survey will serve as a baseline for time-lapse gravity observations made after the beginning of the injection.

The survey results have a good correlation with the regional gravity maps of Daniels et al. (2008). Located at a minimum between two large-scale 15-mGal positive anomalies, the survey measurements complete the regional survey and allow a better definition of the short wavelength content of the gravity signal above the FutureGen storage site (Figure 2.18). At the scale of the survey, the Bouguer anomaly presents several small undulations (1,000−2,000 m in wavelength and 1−2 mGal in amplitude) that can be interpreted as variations in the topography of the Precambrian basement. There is no indication of any major subsurface discontinuities within the site.

Figure 2.19 presents forward modeling of the Bouguer anomaly along a 250-km-long southwest-northeast (W-SW to E-NE) profile passing through the deepest wells of the region. The observed short wavelength anomalies are well explained by variations in the basement topography (d = 2.70 g/cm^3) overlaid by a less dense Mount Simon Sandstone (d = 2.46); background density being 2.67. The long wavelength anomalies are linked to deep denser mafic intrusions (d = 2.80) in the basement as observed in other parts of the Illinois Basin and confirmed by the observed magnetic anomalies (not represented here). Other interpretations could also be valid but this one makes the most of sense especially when one looks at the importance of this phenomenon at the regional scale. Note the thickening of Mount Simon to the east of the stratigraphic well, which is compatible with the growth fault identified on the L100 seismic profile.

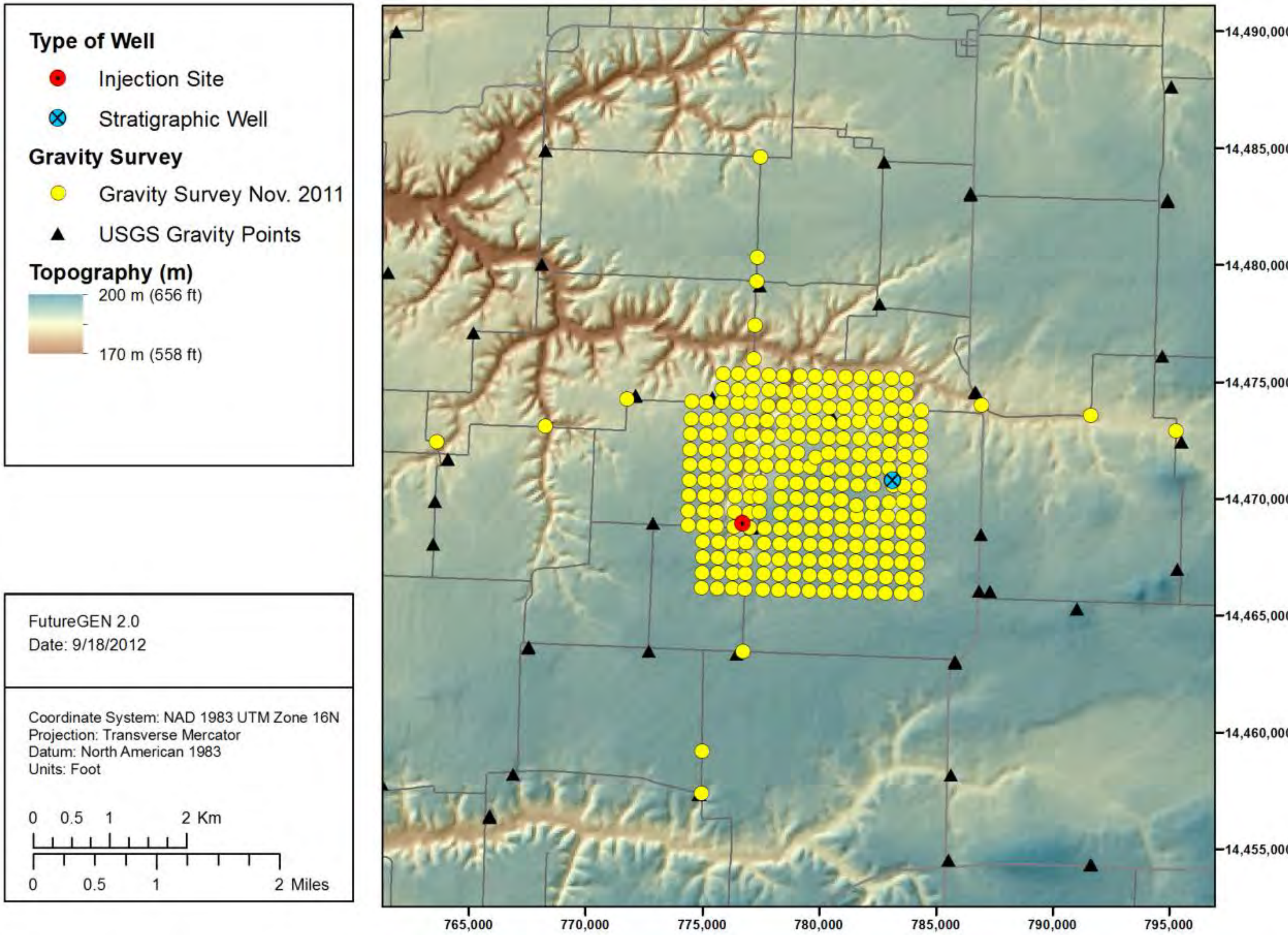

Figure 2.17. Gravity and GPS Stations for the 2011 Survey. Black triangles represent existing USGS gravity stations.

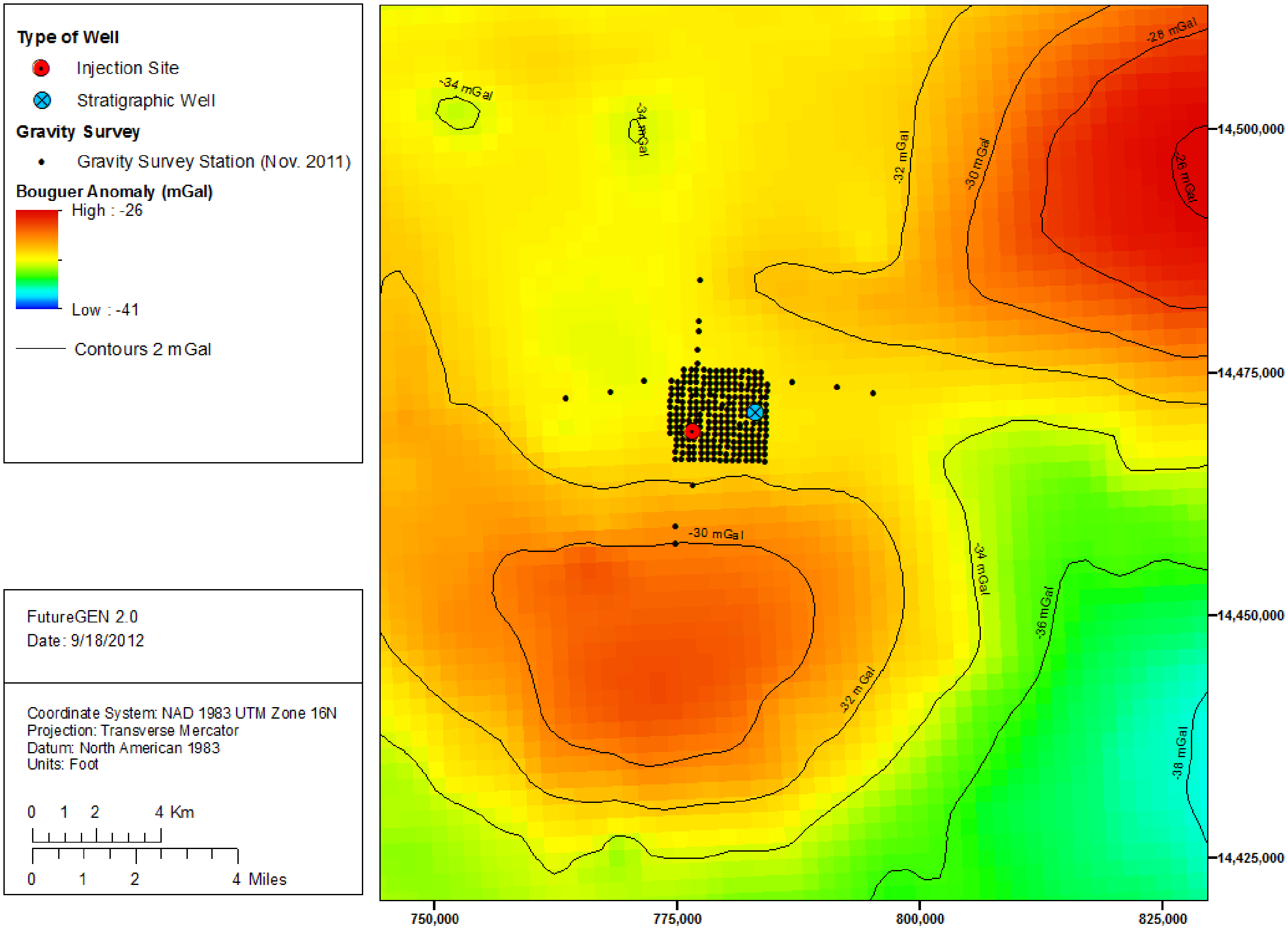

Figure 2.18. Overlay of Local Bouguer Gravity with USGS Regional Survey (regional survey data from Daniels et al. 2008).

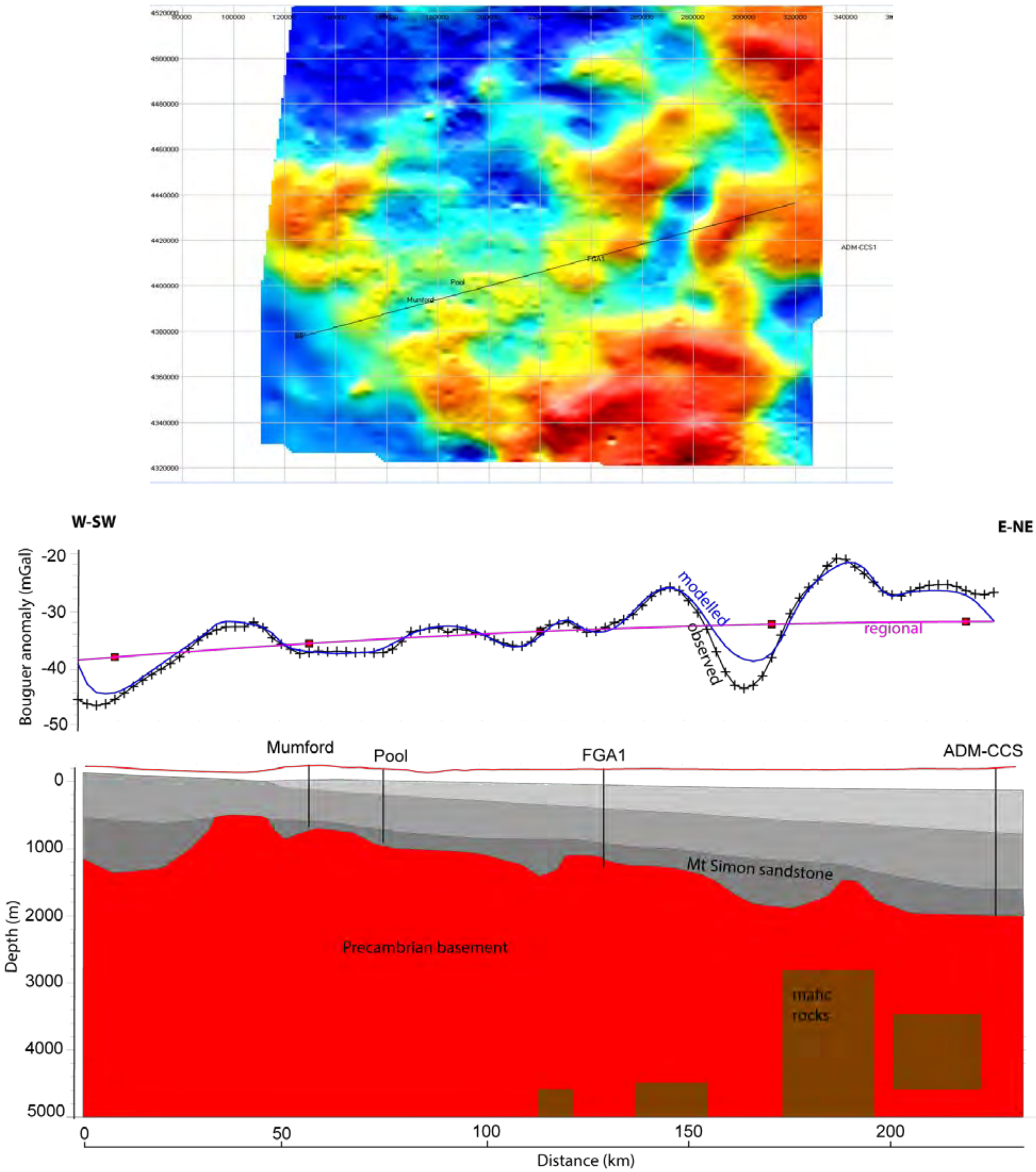

Figure 2.19. Regional WE Bouguer Anomaly Profile. Bottom: modeled depth cross section with Precambrian basement in red and Paleozoic rocks in grays. Middle: Bouguer anomaly in milliGals (black line = observed; blue line = modeled; pink = regional). Top: Bouguer anomaly map with location of the profile and of the deepest wells used to constrain the modeling.

2.4 Geomechanical Information

Geomechanical properties discussed in this section are derived from laboratory analyses of whole core and rotary side-wall cores from the stratigraphic well, as well as from acoustic and density log data, and the azimuth of open fractures, drilling-induced fractures, and well-bore breakout as observed in the resistivity-based image log. Geomechanical well logs, computed from shear and compressional components of the crossed dipole sonic log, provide information about the variability of Young's modulus ("rock stiffness") and Poisson's ratio ("rock compressibility"). Triaxial laboratory tests, conducted on vertical plugs from whole core, provide estimates for elastic moduli, and will be used to calibrate the geomechanical logs calculated from the wireline geophysical logs.

This section first addresses general mechanical properties of the rock layers encountered in the stratigraphic well, including any indications of faults, fractures, fissures, or karst. Next the available information about the stress tensors, or the nature of earth stress, is discussed for the stratigraphic well and how this information compares with regional stresses. Finally, the available geomechanical data are reviewed, specific to the injection zone and confining layers.

Various supportive geomechanical data were collected, but there are no available "mini-frac" or leak-off tests to directly measure fracture pressure in either the injection or confining zones. Mini-frac or leak-off data are required to definitively calculate site-specific fracture gradients, and to produce high-confidence failure plots, fault slip tendency estimates, and critical pore fluid pressure increase estimates. All of these tests will be realized in 2013 during the second phase of the project. However, the log and core data do allow for a determination of site-specific stress orientation and relative magnitudes of stress within the subsurface, a preliminary assessment of geomechanical properties, and provide a good comparison with regional data. Because of the limited quantitative data, regional geomechanical data were used as parameter input for the design and numerical simulations (Chapter 3.0).

2.4.1 Karst

There are no indications of karst topography, sinkholes, or voids in the near surface, but there is evidence of Knox-age karst features (sensu Freiburg and Leetaru 2012) in the subsurface Potosi Dolomite between 2,839 and 3,074 ft (865–937 m) bgs. The paleokarst expression includes the development of vuggy porosity, as observed in rotary side-wall cores and in the resistivity-based image log, as well as lost circulation zones during the drilling of the stratigraphic well. This zone is above the Franconia secondary confining layer. The buried Knox paleokarst zone is known regionally and was encountered in the ADM CCS wells at Decatur, Illinois (Freiburg and Leetaru 2012).

There is no evidence of tectonic fracture zones, and there are very few natural fractures intersecting the stratigraphic well bore, as indicated in the resistivity-based image log and in the 211 ft of whole core. The azimuth of the maximum horizontal stress in the stratigraphic well, as indicated by the azimuth of the dipole sonic fast shear wave, and by the azimuth of the sparse natural fractures detected by image logs, is N79.9°E, over the entire sedimentary interval, as logged from 4,416 (1,346 m) to 596 ft (182 m) bgs. Natural fractures that are parallel to the maximum horizontal stress are more likely to be transmissive (Streit and Hillis 2004).

2.4.2 Local Crustal Stress Conditions

Geomechanical analysis of sonic and density log data from the stratigraphic well, together with analysis of natural fractures, drilling-induced fractures, and well-bore breakout as observed in the resistivity-based image log (Schlumberger's Formation Microimager log) allow a partial determination of earth stress conditions within the well bore. A summary of the findings is as follows: the azimuth of the maximum horizontal stress (S_{hmax}) is N 79.9°E and has a much larger magnitude than the minimum horizontal stress (S_{hmin}). The lithostatic (vertical or Sv) stress is larger than S_{hmin} in both injection zones and confining layers indicating that the stress regime is not inverse. However in the absence of quantitative estimate of S_{hmax}, it is not possible to state whether Sv is greater than S_{hmax} (normal stress regime) or not (strike-slip stress regime). Uncalibrated geomechanical stress properties logs were calculated from the density log and the compressional and shear wave sonic log data. These geomechanical logs indicate there is strong stress anisotropy. These uncalibrated geomechanical logs will later have been calibrated over the cored interval with six triaxial core-plug tests. There are no indications of faults or tectonic fracture zones within the injection zone or in the primary or secondary confining zones, and the normal stress regime appears to be valid for the entire sedimentary logged interval from 4,416 (1,346 m) to 596 ft (182 m). Details of the basic determination of the stress regime follow.

2.4.2.1 Determination of Vertical Stress S_v from Density Measurements

The magnitude of the vertical stress (S_v) can be represented by the weight of the overburden (i.e., lithostatic pressure) and can be calculated by integration of wireline log-derived rock densities from the surface to the depth of interest (Zoback et al. 2003). Where density log data are not available (depth <596 ft [182 m]), Zoback et al. (2003) are followed in assigning a density of 2,300 kg/m^3 for siltstones, shales, and sandstones (typical lithologies of the shallow Pennsylvanian section at the site). The overburden gradient, calculated from these data is 1.1 psi/ft. Lithostatic pressures (S_v) at the top of the reservoir (base of primary confining zone), top of primary confining zone, and at the top and base of the secondary seals are shown in Table 2.8.

Table 2.8. Lithostatic Pressure at Important Interfaces

Unit	MPa	psi
Top of Franconia confining zone	3.36	3,388
Top of Ironton Saline Aquifer	25.34	3,675
Top of Proviso confining zone	26.15	3,792
Top of Elmhurst reservoir	29.9	4,249

2.4.2.2 Maximum and Minimum Horizontal Stress Azimuth from Resistivity-Based Image Logs

In vertical wells, the occurrence of breakout or tensile fractures usually implies that S_{hmin} is the minimum principal stress and that there are large differences between the two horizontal stresses S_{Hmax} and S_{hmin}. The azimuths of the maximum and minimum horizontal stresses are indicated by the azimuth of the induced tensile fractures and the borehole breakout, respectively (Zoback et al. 2003).

Both well-bore breakouts and tensile fractures are present in the borehole image logs. The calculated azimuth of borehole breakout minimum horizontal stress (S_{hmin}) is 169.9°N; the azimuth of maximum horizontal stress (S_{Hmax}) is 79.9°N. The azimuth of maximal horizontal stress (S_{Hmax}) in the stratigraphic well is consistent with regional stresses (Helmotz Centre Potsdam – GFZ 2012). However in the absence of quantitative determination of S_{Hmax}, it is impossible to state whether it is greater or not than Sv.

In summary, data from the stratigraphic well indicate that vertical lithostatic stress (S_v) is greater than the minimum horizontal stress (S_{hmin}). This indicates that the site is not in an inverse stress regime, and any undetected faults, if present, would be either normal or strike-slip faults (Table 2.9). The basic stress analysis data did not indicate any change in stress regime from the base of the Mount Simon to the top of the logged interval (4,416 [1,346 m] to 596 ft [182 m] bgs. Data are insufficient at this stage of analysis to be able to quantify the horizontal components of stress and thus distinguish between normal and strike-slip regimes.

Table 2.9. Relation of Principal Stresses to Fault Types (Zoback 2007)

	Stress		
Regime	S_1	S_2	S_3
Normal	S_v	S_{Hmax}	S_{hmin}
Strike-Slip	S_{Hmax}	S_v	S_{hmin}
Reverse	S_{Hmax}	S_{hmin}	S_v

2.4.3 Elastic Moduli and Fracture Gradient

The elastic moduli (or constants) include bulk modulus, Poisson's ratio, shear modulus, and Young's modulus, and characterize the properties of a rock that define how rock deforms when undergoing stress and how the rock recovers after the stress is released.

Fracture pressure is the pressure above which fluid injection will cause a formation to undergo brittle failure, i.e., to fracture hydraulically. Fracture-closing pressure is the pressure required to keep an existing fracture open, or to cause an existing fracture to widen. Fracture gradient is the pressure increase (change) per unit of depth that would initiate the onset of brittle rock failure.

Elastic moduli and fracture gradients were estimated from limited core analysis samples. Triaxial geomechanical tests were conducted on eight vertical core plugs from the cored intervals of the stratigraphic well. Table 2.10 lists the measured and calculated results of elastic moduli for the proposed injection zone and for the Precambrian basement. Table 2.11 shows the resulting calculated fracture gradients. For each table, samples 1 and 2 are from the Lombard member; samples 3 and 4 are from the Elmhurst; samples 5 and 6 are from the uppermost Mount Simon Sandstone; sample 7 is from the basal part of the Mount Simon, and sample 8 is from the Precambrian basement.

For comparison with regional data, Table 2.12 lists fracture gradients and elastic moduli determined for the Mount Simon at the ADM sequestration site at Decatur, Illinois, and at other Illinois Basin locations.

Table 2.10. Elastic Moduli Parameters from Triaxial Tests on Vertical Core Plugs in the Injection Interval and Precambrian Basement

Sample Number	Depth (ft)	Formation	Confining Pressure (psi)	Bulk Density (gm/cm^3)	Compressive Strength (psi)	Young's Modulus (10^6 psi)	Poisson's Ratio
1	3788.10	Lombard member	980	2.41	19,731	4.97	0.22
2	3802.80	Lombard member	1820	2.69	25,605	4.56	0.23
3	3867.90	Elmhurst member	890	2.25	9820	0.88	0.20
4	3887.30	Elmhurst member	750	2.28	7655	1.82	0.21
5	3929.10	Mt Simon SS.	770	2.42	18,076	2.89	0.23
6	3937.40	Mt Simon SS.	840	2.41	11,430	1.54	0.23
7	4401.90	Mt Simon SS.	1100	2.34	11,336	1.49	0.23
8	4434.50	Basement	1320	2.63	40,994	9.11	0.29

Table 2.11. Minimum Horizontal Stress and Fracture Gradient Calculated from Triaxial Tests (the red line represents the injection zone.)

Sample Number	Depth(ft)	Overburden Stress (psi)	Pore Pressure (psi)	Biot's Constant	Min. Horizontal Stress	Fracture Gradient (psi/ft)	Fracture Toughness (psi-in0.5)
1	3788.10	4167	1667	0.69	2533	0.669	1913
2	3802.80	4183	1673	0.70	2579	0.678	1836
3	3867.90	4255	1702	0.66	2502	0.647	802
4	3887.30	4276	1710	0.67	2560	0.659	1156
5	3929.10	4322	1729	0.71	2679	0.682	1464
6	3937.40	4331	1732	0.71	2682	0.681	1069
7	4401.90	4842	1937	0.70	2987	0.679	1050
8	4434.50	4878	1951	0.84	3301	0.744	2642

Table 2.12. Range of Geomechanical Properties (after EPA 2011, unless otherwise noted)

Hydrogeologic Unit	Fracture Gradient (psi/ft)	Young's Modulus (psi)	Poisson's Ratio	Bulk Modulus (psi)	Shear Modulus (psi)
Mount Simon Sandstone	0.57[(a)] to 0.715[(b)]	2.33-7.86E6[(c)]	0.17-0.36[(c)]	NA	NA

NA = Not available.
(a) EPA (1994).
(b) After EPA 2011 and 40 CFR 146.88.
(c) After Sminchak 2011.

2.4.3.1 Injection Zone Fracture Pressure

Geophysical logs from the stratigraphic well provide general estimates of geomechanical anisotropic elastic properties. Triaxial test data for log calibration are limited to six vertical plugs within the cored intervals, and validation of well-log and core data using mini-frac data or leak-off tests is still required to acquire accurate values for elastic parameters and fracture gradients. Fracture gradient (Table 2.11) ranges for the injection zone were calculated from 0.647 to 0.682 psi/ft. Although no step-rate injection tests or leak-off test data are currently available for the injection zone, these data will be obtained when the injection wells are drilled.

At the CCS#1 well at Decatur, about 65 mi east of the stratigraphic well, a fracture pressure gradient of 0.715 psi/ft was calculated for the base of the Mount Simon Sandstone formation using a step-rate injection test (EPA 2011). Additional comparison of regional fracture gradients is provided in the *Determination of Maximum Injection Pressure for Class I Wells in Region 5* (EPA 1994), which lists a default fracture gradient of 0.57 psi/ft for the Mount Simon Sandstone.

Based on these considerations, a pressure gradient of 0.65 psi/ft is suggested to model the injection-zone fracture gradient.

2.4.3.2 Confining Zone Fracture Pressure

Elastic moduli calculated from triaxial core tests on two vertical core samples from the lowermost Lombard member are presented in Table 2.13, and estimations of minimum horizontal stress and fracture gradient calculated from triaxial tests are presented in Table 2.14. Note that the lower Lombard has lithologies and rock properties that are transitional from the porous and permeable Elmhurst sandstones to lithologies and properties of the actual confining part of the upper Lombard. Thus, these moduli, stress estimates, and fracture gradients are not representative of the confining zone. Although no step-rate tests or leak-off tests are currently available for the primary confining zone in the stratigraphic well and no whole core is currently available from the Proviso member or from the upper part of the Lombard member, these data will be obtained when the injection wells are drilled.

Field analog data may be more representative of confining zone properties. The elastic moduli and fracture gradient for the Eau Claire confining zone at the CCS#1 well at Decatur, Illinois, are presented in Table 2.15.

Table 2.13. Elastic Moduli Parameters from Triaxial Tests of Core from the Lowermost Part of the Lombard Member

Depth (ft)	Member	Confining Pressure (psi)	Bulk Density (gm/cm^3)	Compressive Strength (psi)	Young's Modulus (10^6 psi)	Poisson's Ratio
3788.10	Lombard	980	2.41	19731	4.97	0.22
3802.80	Lombard	1820	2.69	25605	4.56	0.23

Table 2.14. Minimum Horizontal Stress and Fracture Gradient Calculated from Triaxial Tests

Sample Number	Depth(ft)	Overburden Stress (psi)	Pore Pressure (psi)	Biot’s Constant	Minimum Horizontal Stress	Fracture Gradient (psi/ft)	Fracture Toughness (psi-in 0.5)
1	3788.10	4167	1667	0.69	2533	0.669	1913
2	3802.80	4183	1673	0.70	2579	0.678	1836

Table 2.15. Range of Eau Claire Geomechanical Properties in the CCS#1 Well, Decatur Illinois (after EPA 2011)

Hydrogeologic Unit	Fracture Gradient (psi/ft)	Young's Modulus (psi)	Poisson's Ratio	Bulk Modulus (psi)	Shear Modulus (psi)
Eau Claire Carbonate/Siltstone (Upper Unit-Proviso)	NA	NA	NA	NA	NA
Eau Claire Siltstone/Shale (Lower Unit 1)	0.93 to 0.98	5.5E6	0.27	3.92E6	2.17E6

NA = Not available.

2.5 Seismic History of Region

In Illinois, most of the seismicity occurs in the southern and southeastern part of the state where two seismic zones (Wabash Valley and New Madrid) are found. Central Illinois is an area that has been historically low in earthquakes or seismicity (Figure 2.20). Statewide, the largest recorded earthquake (magnitude 5.4) occurred on April 18, 2008, in the southeastern part of the state; it caused minor structural damage. The closest known earthquake to the FutureGen 2.0 Project site (Intensity VII, magnitude 4.8 – non-instrumented record) occurred on July 19, 1909, approximately 28 mi (45 km) north of the site; it caused slight damage. Most of the events in Illinois occurred at depths greater than 3 km (1.9 mi) (Figure 2.20).

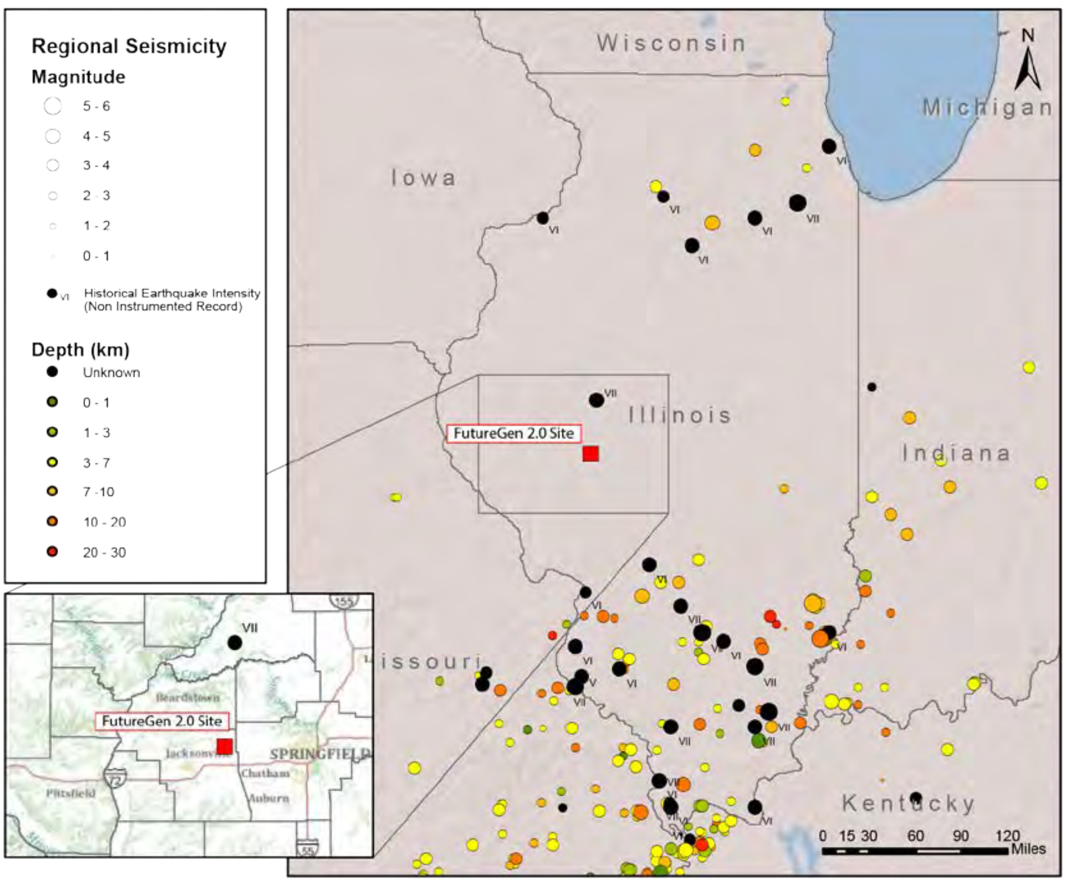

Figure 2.20. Regional Historic Earthquakes (data from USGS 2012a, b)

There is a 2 percent probability that the peak ground acceleration (G) due to seismic activity will exceed 9 percent G within 50 years (Figure 2.21; USGS 2008).

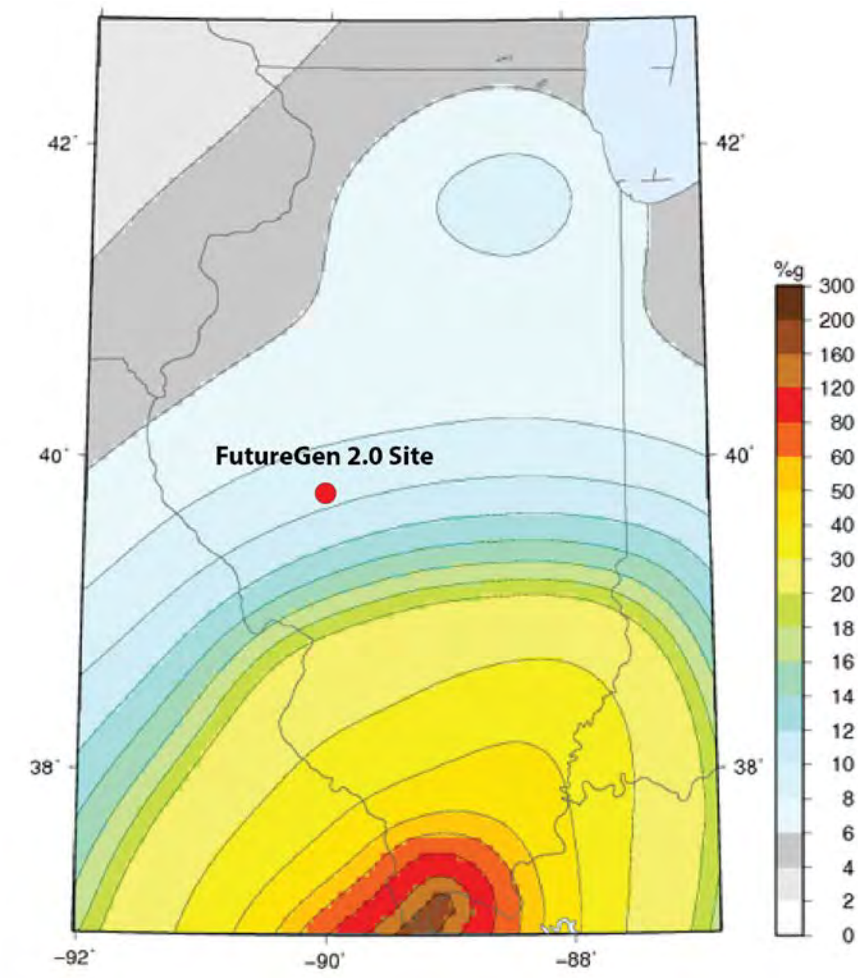

Figure 2.21. Earthquake Risk for Illinois Given as Maximum Accelerations with a 2 Percent Probability of Being Exceeded Within 50 Years (modified from USGS 2008)

The general absence of seismicity in historical times within west-central Illinois suggests a lack of appreciable active faulting in this area.

2.5.1 Regional Topography and Geomorphology

West-central Illinois is located within the low-relief Springfield Plain underlain by pre-last-glacial till (Figure 2.22) of the Glasford Formation. These deposits were laid down during the Illinoisan glacial episode more than 120,000 years ago (Kolata and Nimz 2010, p. 223). The Springfield Plain lies beyond the area covered with glaciers during the most recent cycle of glaciation (Wisconsin episode; green area in Figure 2.22). The topography of the region is predominantly farmlands ranging from about 400 ft (122 m) in elevation along the Illinois and Mississippi river valleys to 700 ft (213 m) along some drainage divides to the east.

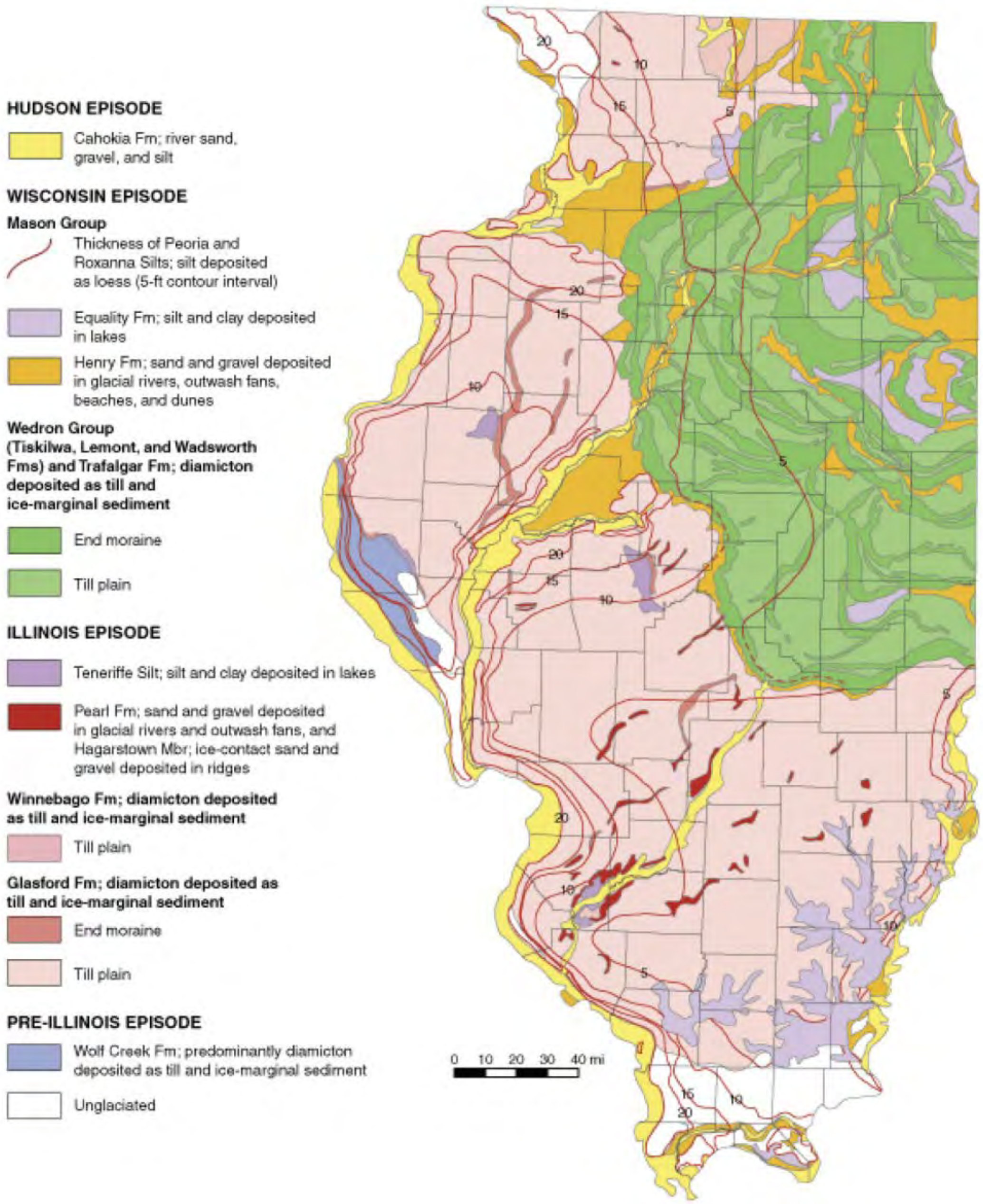

Figure 2.22. Surficial Quaternary Deposits of Illinois (modified from ISGS 2012d)

2.5.2 Site Surface Topography

The surface topography at the proposed Morgan County CO_2 storage site lies between 590 and 620 ft (180 and 189 m) above mean sea level (MSL). Surface drainage is to the north-northeast toward the Illinois River through Indian Creek, the nearest perennial stream (Figure 2.23). About 75 to 125 ft (23 to 38 m) of middle-to-early Pleistocene glacial drift and glaciolacustrine deposits (Glasford Formation) disconformably overlie the Pennsylvanian bedrock in the vicinity of the proposed CO_2 storage site (Figure 2.25 in Section 2.6.1). The uppermost bedrock consists of thinly bedded shale, siltstone, sandstone, limestone, and coal.

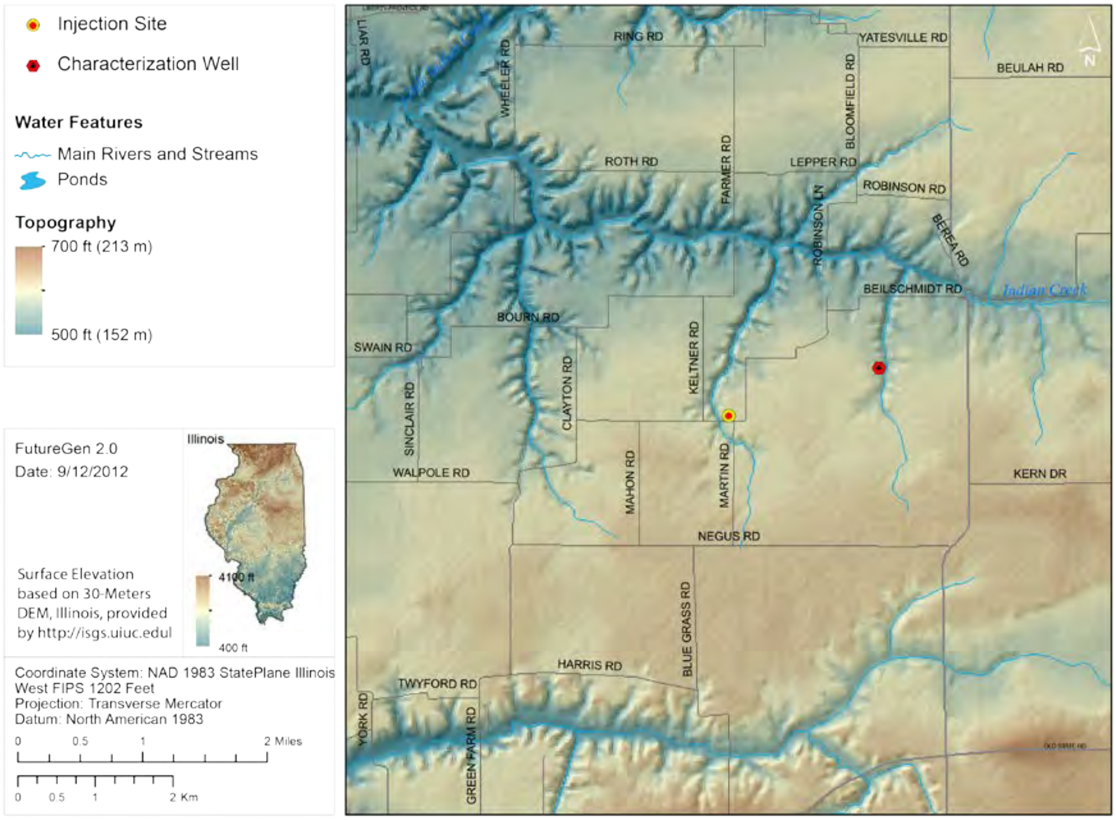

Figure 2.23. Surface Topography and Drainage

2.6 Groundwater

Several aquifers are present at the proposed Morgan County storage site. These aquifers are underground layers of water-bearing permeable rock that are separated from one another by less permeable rock layers. Not all of the aquifers contain potable water and in general the salinity of the aquifers increases with depth. At the proposed Morgan County site, drinking water is developed from the Quaternary-age glacial sediments (approximately 150 ft [46 m] bgs). Although this surficial zone is the hydrogeologic unit from which all known water-supply wells are completed, for the purpose of the permit application, the deeper St. Peter Sandstone is considered the lowermost USDW. The St. Peter Sandstone is considered the lowermost USDW, because the measured TDS content from this unit at the FutureGen stratigraphic well is 3,700 mg/L, which is below the regulatory upper limit of 10,000 mg/L for drinking water aquifers. A summary of both potable and nonpotable and brackish aquifers is presented below.

2.6.1 Surficial Aquifer System

Domestic, municipal, and agricultural water-supply wells in Morgan County typically do not exceed 100 ft (46 m) in depth, and only a few wells are deeper than 75 ft (23 m) bgs. All water-supply wells within a 20-mi^2 area are from the Quaternary glacially derived sediments that overlie Pennsylvanian bedrock (ISGS 2012b). While much of the Quaternary section consists of fine-grained, low-permeability clay and silt, lenses of glacial outwash sand and gravel are also locally present, particularly within paleo-stream valleys denoted by greater glacial drift thicknesses as shown in Figure 2.24. The variability of the different facies within the Quaternary sediments is illustrated in a cross section in Figure 2.25.

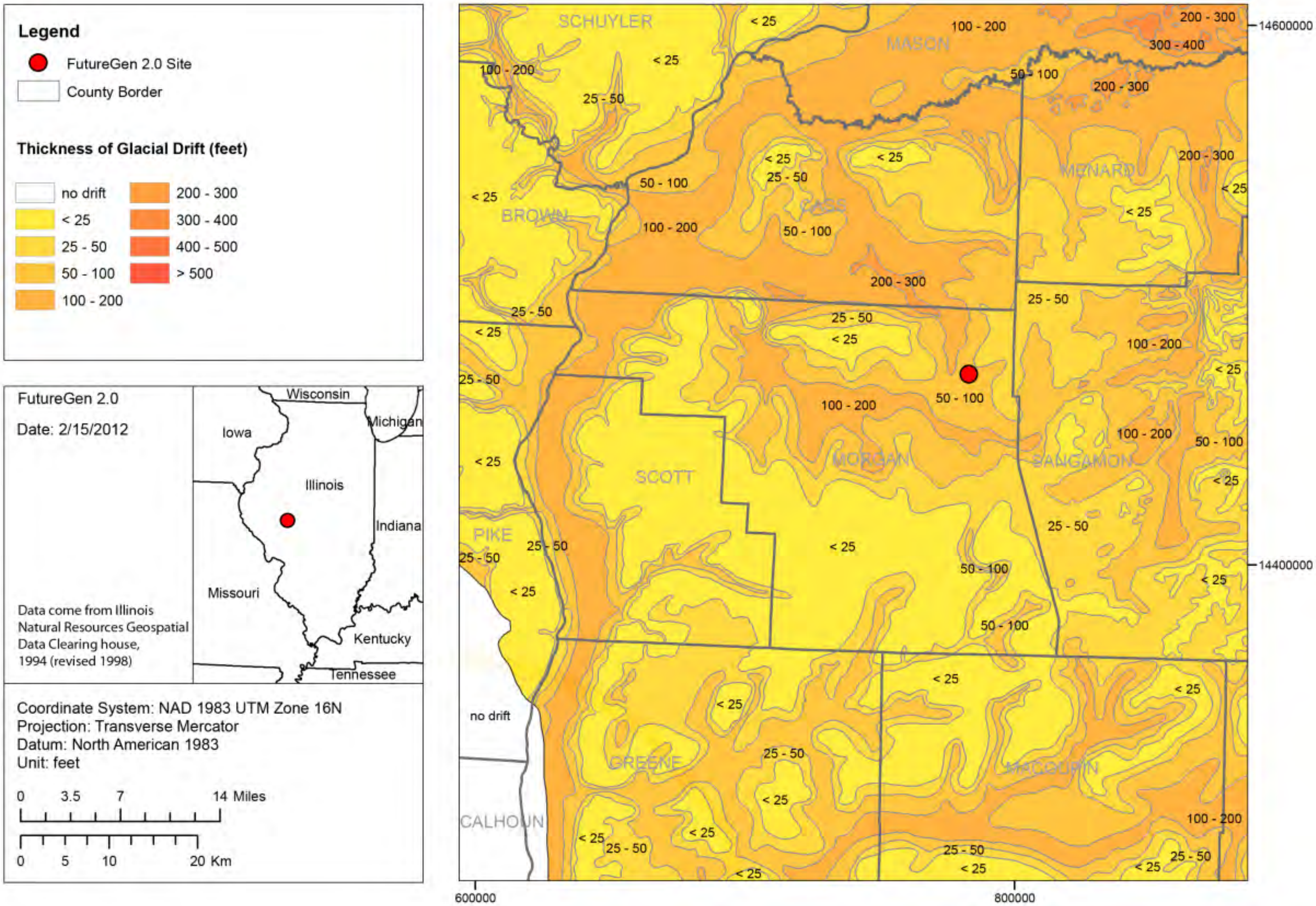

Figure 2.24. Thickness of Unconsolidated Pleistocene Glacial Drift in Morgan and Adjacent Counties (based on data from ISGS 2012b)

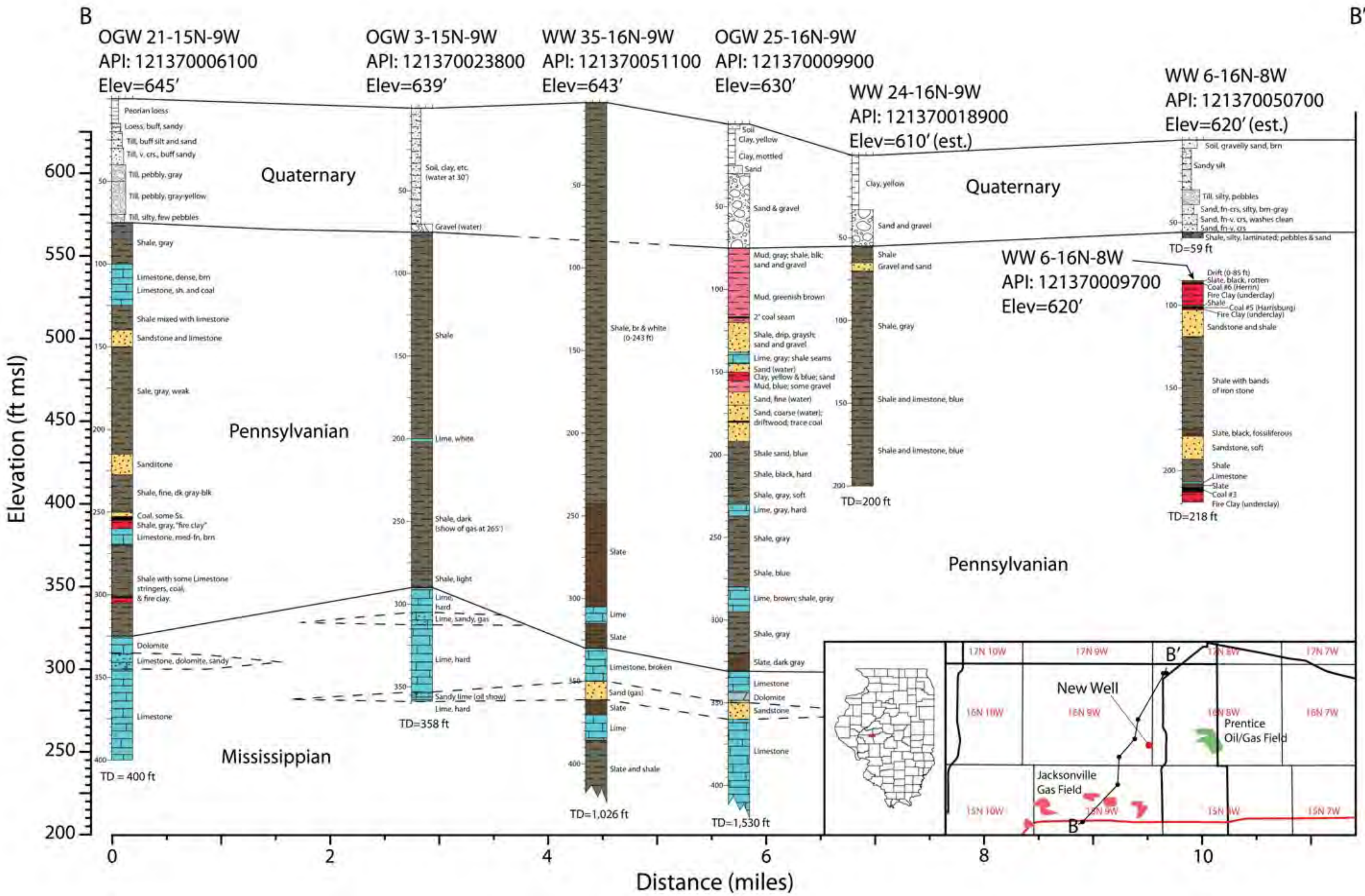

Figure 2.25. Variability of Quaternary Sediments and Shallow Pennsylvanian Rocks in the Vicinity of the Proposed Morgan County CO_2 Storage Site (based on data from ISGS 2011).

Detailed potentiometric surface maps and information about local groundwater flow direction are sparse for the shallow unconfined sand/gravel aquifer system at the Morgan County CO_2 storage site. However, groundwater flow within the shallow surficial aquifer is expected to conform to the local topography and discharge to local surficial drainages and surface bodies of water. Static water-level data available for water-supply wells in northwest Morgan County area indicate that water-table depth varies depending upon local topography and the seasonal variations in recharge and generally ranges between 5 to 30 ft (1.5 to 9 m) bgs (ISGS 2012c).

A shallow groundwater/well sampling investigation was performed in 2011 on 13 surrounding private/domestic water-supply wells within 1.5 mi (2.4 km) of the FutureGen stratigraphic well (FG1) location (Figure 2.26). All of the wells are shallow (14 to 47 ft [4 to 14 m] deep).

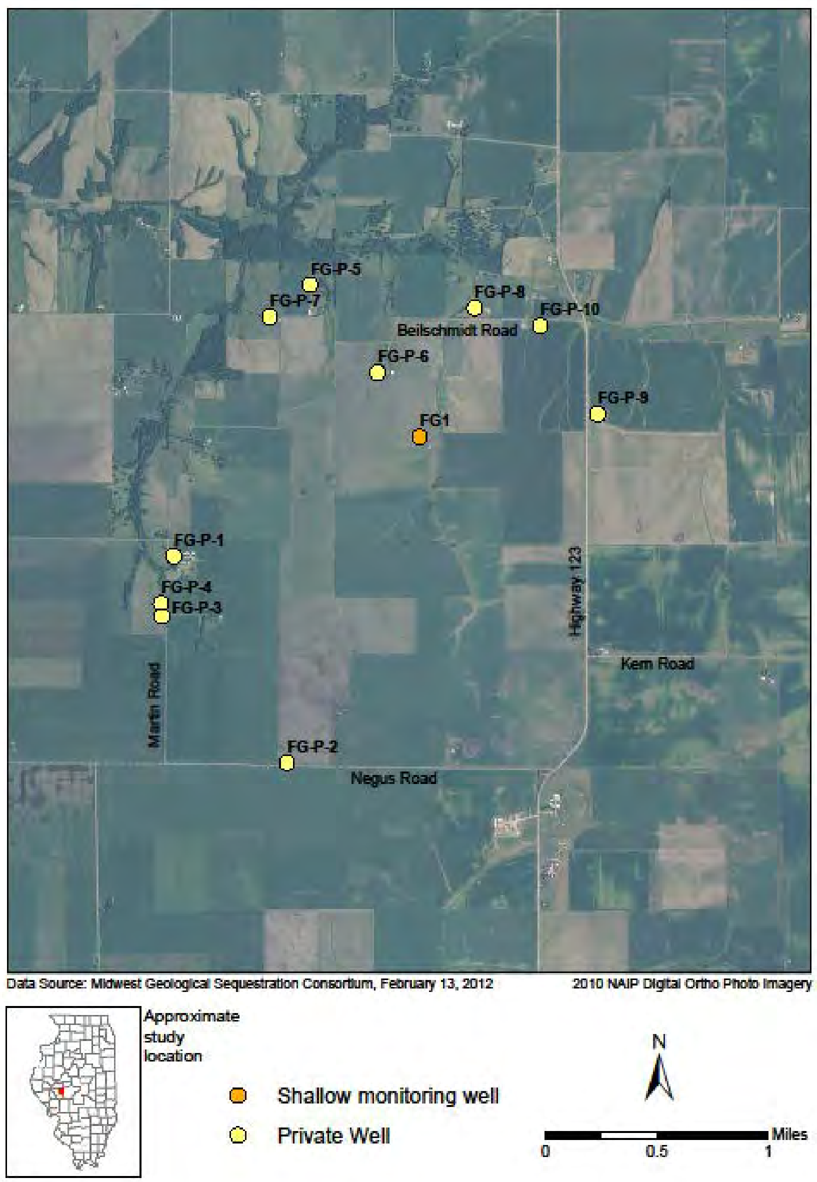

Figure 2.26. Locations of Private/Domestic Water Wells Within 1.5 Mi (2.4 Km) of the Stratigraphic Well (FG1; based on data from ISGS 2012c)

A total of 20 groundwater samples were collected between October 25 and November 10, 2011, including duplicate samples and blanks (Dey et al. in press). General water-quality parameters were measured along with organic and major inorganic constituents. Values of pH ranged from 7.08 to 7.66. Values for specific conductance ranged from 545 to 1,164 µS/cm, with an average of 773 µS/cm. Values of Eh ranged from 105 to 532 mV with an average of 411 mV. Values of dissolved oxygen (DO) ranged from below detection limit to 3.3 mg/L O_2.

Most dissolved inorganic constituent concentrations are within primary and secondary drinking water standards. However, the constituent concentration in water is elevated with respect to iron (Fe), manganese (Mn), nitrate (NO_3), and TDS. In some cases these constituents exceed the EPA secondary standards.

2.6.2 Upper-Bedrock Aquifer System

The shallow bedrock aquifers are discussed in descending stratigraphic order (i.e., youngest to oldest), and range from Pennsylvanian-aged bedrock units to the older Cambrian-aged Mount Simon Sandstone. The fluid salinity within these formations generally increases with depth and correspondingly their use as potential potable aquifers also diminishes.

Pennsylvanian-aged bedrock units (Kolata 2005) in Morgan County consist principally of shale with occasional sandstone lenses and do not offer potential as sources of groundwater except for the occurrence of discontinuous, thin beds of sandstone or fractured limestone that may yield small, domestic supplies (Woller and Sanderson 1979).

Mississippian-aged strata regionally dip to the east (Figure 2.27) at about 10 to 40 ft/mi in Morgan County (Woller and Sanderson 1979). The Salem and Burlington-Keokuk limestones are the principal, but relatively limited, Mississippian aquifers because their yield capacity depends on the abundance and interconnection of fractures and crevices within the rock that are intersected by the well (Woller and Sanderson 1979). The younger Salem Limestone occurs at a depth ranging from 175 to 650 ft (53 to 198 m) bgs in Morgan County and exhibits marginally adequate yields that become more saline with depth. Data from the Illinois State Water Survey (ISWS)[1] contain water-quality data for three bedrock wells in Morgan County. The TDS concentrations for the three Morgan County wells range from 3,894 to 10,420 mg/L.

A study conducted in 1978, found no water-supply wells were developed within the shallow bedrock aquifers in Morgan County (Woller and Sanderson 1979), although Pennsylvanian and Mississippian bedrock units were reported as water supplies for domestic use in Morgan and adjacent counties (Bergstrom and Zeizel 1957; Selkregg and Kempton 1958; Gibb and O'Hearn 1980).

Lack of primary or secondary porosity appears to be the limiting factor for aquifer development in bedrock shallower than 500 ft (152 m) bgs. No aquifers or aquifer materials have been identified in the Pennsylvanian or Mississippian bedrock near the site and there are no municipal or domestic water-supply wells that develop groundwater from the shallow bedrock aquifers within the preliminary AoR.

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[1] Obtained from the ISWS Online Database, http://www.isws.illinois.edu/data/gwdb, accessed in April 2011.

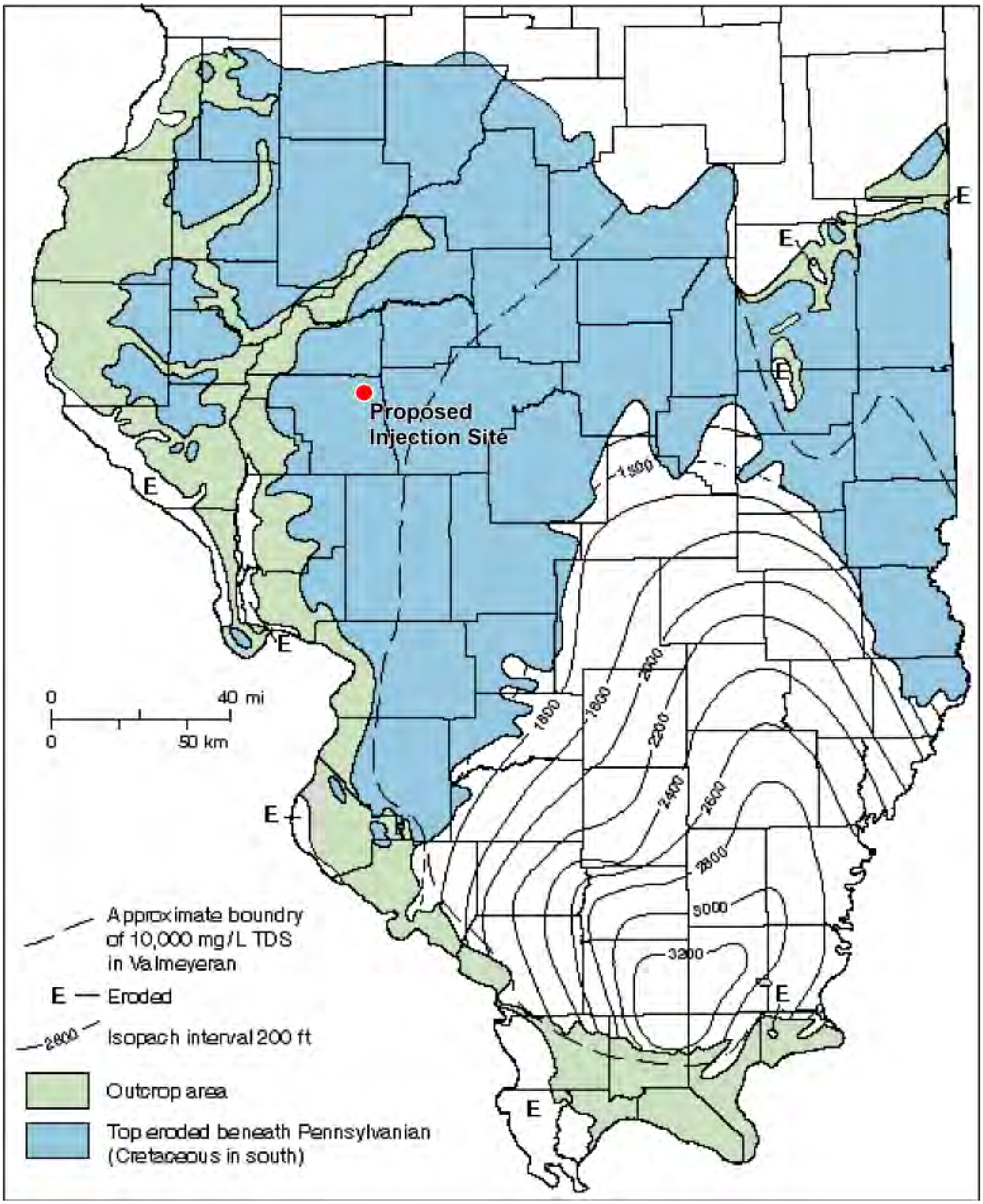

Figure 2.27. Thickness and Distribution of Mississippian Aquifers (after Willman et al. 1975) and the Boundary for 10,000 mg/L TDS in the Middle Mississippian Rocks

2.6.3 Lower-Bedrock Aquifer System

At least four, deep (>500 ft [>152 m]), aquifers are present beneath the proposed Morgan County CO_2 storage site. From youngest to oldest these are the Ordovician St. Peter, New Richmond, Cambrian Ironton-Galesville, and the Elmhurst/Mount Simon Sandstone intervals (see Figure 2.1). Of the four major lower-bedrock aquifers only the shallowest, the Ordovician St. Peter Sandstone, has been considered for possible, future water-supply use (Kolata and Nimz 2010). None of these deeper, lower-bedrock aquifers below the St. Peter has been used for water supply within or near Morgan County because of elevated salinities, in combination with their depths which limit economic pumping.

Illinois Basin-scale hydrogeologic models (e.g., Bethke and Marshak [1990], Gupta and Bair [1997], and Birkholzer et al. [2007]) indicate elevated freshwater heads within the lower-bedrock aquifer system varying from about 650 ft (198 m) above MSL to 165 ft (50 m) below MSL, with hydraulic head gradients of ~0.0003. Regional approximations of the potentiometric surface (hydraulic head) and generalized flow directions for the deeper lower-bedrock aquifers in the Illinois Basin have also been reported by Visocky et al. (1985) and Mandle and Kontis (1992). However, these studies have focused on the northern portion of Illinois, where extensive water-supply production exists in these deeper bedrock aquifer systems.

2.6.3.1 St. Peter Sandstone

The St. Peter Sandstone has been used for injection and storage of natural gas at the Waverly Storage Field (16 mi [26 km] southeast of the proposed Morgan County CO_2 storage site). At the Waverly Storage Field the groundwater salinity of the St. Peter Sandstone is 2,778 mg/L TDS (Buschbach and Bond 1974; Weiss et al. 2009). A fluid sample collected from this aquifer during installation of the stratigraphic well resulted in a laboratory-measured TDS value of 3,400 mg/L and field parameter values of 7.91 and 5,910 μS/cm for pH and electrical conductivity, respectively. Because the dissolved solids content near the proposed storage site was measured at below the upper regulatory limit of 10,000 mg/L for potable aquifers, for the purposes of this UIC permit application, the St. Peter Sandstone is considered to be the lowermost federal USDW. The State of Illinois, however, does not recognize the St. Peter Sandstone as a suitable potable water source at this location.

2.6.3.2 New Richmond Sandstone

The New Richmond Sandstone aquifer occurs between a depth of 2,346 and 2,448 ft (715 and 746 m) within the FutureGen stratigraphic well. No fluid samples were collected from this lower-bedrock aquifer unit.

2.6.3.3 Ironton-Galesville Sandstone

The first bedrock aquifer above the Eau Claire confining zone in Morgan County is the Cambrian Ironton-Galesville Sandstone. Although the Ironton-Galesville Sandstone serves as a water source in northern Illinois where it may reach a thickness of 200 ft (61 m) (Buschbach and Bond 1974; Willman et al. 1975), it is not used as a water-supply source in Morgan or surrounding counties. Regionally, this aquifer system includes two separate lithostratigraphic formations—the Galesville and Ironton formations; the former sandy dolomite is in places separated by a minor conformity from the latter overlying dolomitic sandstone (Willman et al. 1975). Within the FutureGen stratigraphic well, the top of the Ironton-Galesville Sandstone occurs at a depth of 3,300 ft (1,006 m) bkb and is 139 ft (42 m) thick. Little information is available about the potentiometric surface of the Ironton-Galesville Sandstone in Morgan County because of the lack of surrounding deep well characterization information.

Although no published data specifically address the salinity of the Ironton-Galesville Sandstone in wells in Morgan County, Lloyd and Lyke (1995) indicate (Figure 2.28) that groundwater within the Ironton-Galesville Sandstone at the proposed Morgan County CO_2 storage site is saline. No fluid samples were collected from this lower-bedrock aquifer unit. Calculated salinities, however, based on wireline resistivity survey results and observed temperature conditions, indicate an average salinity concentration of approximately 15,000 mg/L at the FutureGen stratigraphic well location. Similar calculations based on wireline log response results for the Mount Simon Sandstone indicate an average salinity concentration of a about 52,000 mg/L, which compares to a laboratory-measured TDS value of ~47,500 mg/L. This difference in calculated salinity concentration between the Ironton and Mount Simon sandstones supports regional information that the intervening Eau Claire acts as a hydrologic barrier above the combined Elmhurst/Mount Simon injection zone.

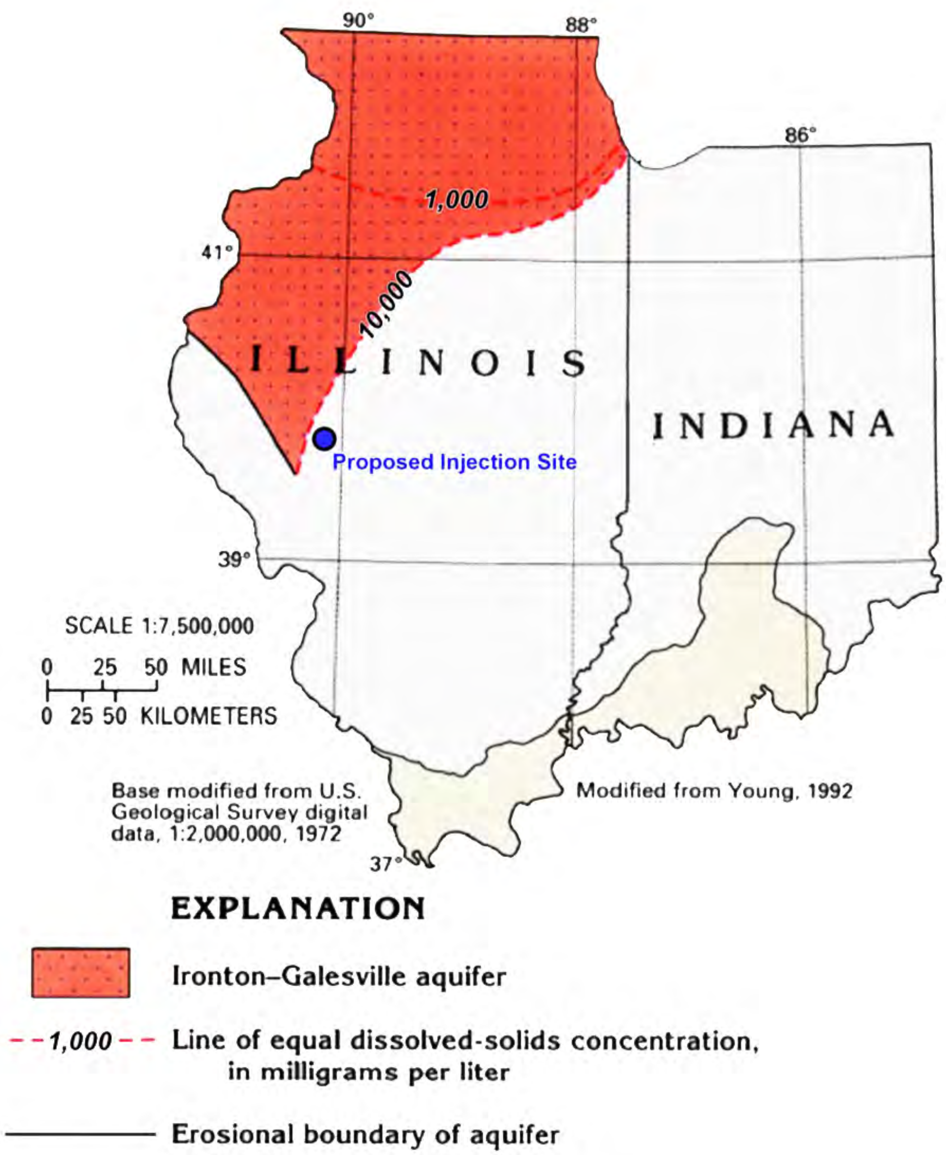

Figure 2.28. Regional Map Showing Limits of Freshwater in the Ironton-Galesville Sandstone Relative to the Proposed Morgan County CO_2 Storage Site (after Lloyd and Lyke 1995)

2.6.3.4 Elmhurst/Mount Simon Sandstone

Visocky et al. (1985) group the overlying Elmhurst member of the Eau Clair Formation with the underlying Mount Simon Sandstone as an individual hydrologic aquifer unit in northern Illinois. In the northern part of the state, the Elmhurst/Mount Simon Sandstone contains fresh groundwater that served as a water supply in northeastern Illinois until the 1970s (Visocky et al. 1985; Young 1992). However, in central Illinois the Mount Simon Sandstone is considered too deep (>3,000 ft [>914 m]) and the groundwater too highly mineralized to be a viable source of drinking water (Kolata and Nimz 2010). Analyses of Mount Simon water samples (Table 2.16) collected in the FutureGen stratigraphic well at a 4,048 ft (1,234 m) with a wireline-deployed formation fluid sampling tool indicated a TDS content of 47,000 mg/L, which is significantly well in excess of the 10,000-mg/L TDS limit recommended for drinking water (40 CFR 144.3). This discrete-depth sample result is consistent with laboratory results obtained from composite sampling of the open borehole Mount Simon section (3,942 to 4,430 ft), which was obtained after significant borehole development (i.e., after pumping >100,000 gal of groundwater from the composite Mount Simon).

Table 2.16. Analyses of Two Formation Fluid Samples from the Mount Simon Sandstone in the Stratigraphic Well

Sample #	Sample Depth (ft bkb)	Elec. Conductivity (μMHOS/cm)	TDS (mg/L)	Salinity (g/kg)
11	4,048	68,600	47,100	44.3
11	4,048	68,600	47,700	44.2

Regionally, Gupta and Bair (1997) presented borehole drill-stem test (DST) data that indicated hydraulic heads within the Mount Simon Sandstone are near hydrostatic levels. Pressure depth measurements for the Mount Simon at the FutureGen stratigraphic well indicate a similar condition with a pressure gradient of ~0.4375 psi/ft, which is slightly higher than hydrostatic conditions (0.4331 psi/ft). Gupta and Blair (1997) also modeled the seepage velocity and flow direction of groundwater in the Mount Simon Formation across an eight-state area that does not include the Morgan County area, but does include eastern Illinois. They concluded that for deep bedrock aquifers, the lateral flow patterns are away from regional basin highs arches, such as the Kankakee Arch, and toward the deeper parts of the Illinois Basin. With respect to vertical groundwater flow, Gupta and Blair (1997) surmised that within the deeper portions of the Illinois Basin, groundwater has the potential to flow vertically upward from the Mount Simon to the Eau Claire, and the vertical velocities are <0.01 in./yr. They estimated that 17 percent of the water recharging the Mount Simon basin-wide migrates regionally into the overlying Eau Claire, while 83 percent flows laterally within the Mount Simon hydrogeologic unit.

Vertical flow potential at the FutureGen site was evaluated based on an analysis of discrete pressure/depth measurements obtained within the pilot characterization borehole over the depth interval of 1,148 to 4,263 ft. Figure 2.29 shows the static pressure/depth measurements obtained within the pilot characterization borehole. Twelve discrete static pressure/depth measurements were obtained using the Schlumberger, wireline conveyed MDT tool, and two static pressure/depth readings were obtained from hydrologic packer tests. As indicated in the figure, representative static pressure measurements over this open pilot borehole interval were obtained for the Silurian Limestone Formation, St. Peter Sandstone, and the Mount Simon Sandstone. For comparison purposes, the normal freshwater hydrostatic pressure gradient (i.e., 0.4331 psi/ft; $\rho_w = 1.000$ g/cm^3 @STP) and brine hydrostatic pressure gradient (based on Mount Simon salinity conditions; 0.4478 psi/ft; $\rho_w = 1.033$ g/cm^3 @STP) are shown for comparison. As indicated in the figure, pressure/depth measurements for both the Silurian and St. Peter test intervals are slightly under-pressured in comparison to the projected, normal freshwater hydrostatic conditions, while pressure/depth measurements exhibit a similar under-pressured relationship in comparison to the projected brine hydrostatic profile.

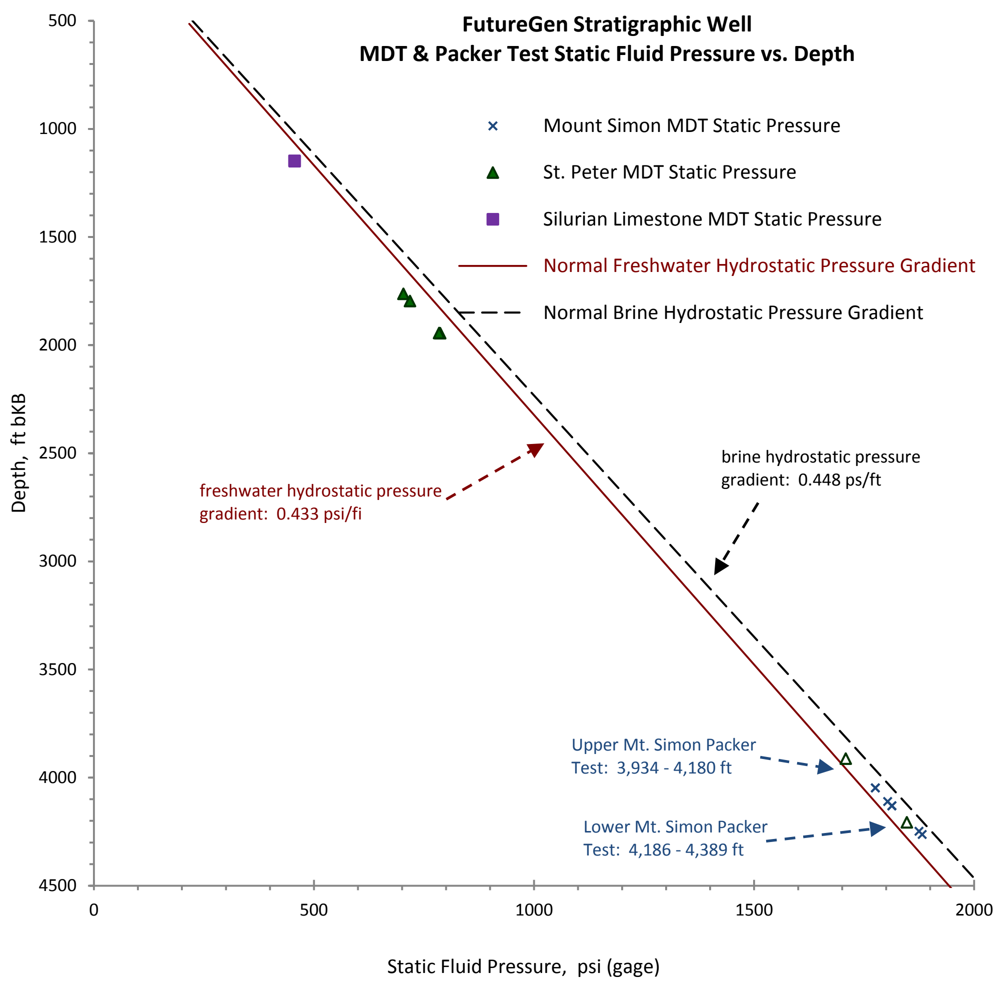

Figure 2.29. Pressure vs. Depth Profile Relationships Within the FutureGen Stratigraphic Well

To assess the vertical flow potential between the Mount Simon and the overlying St. Peter (the lowest USDW) formations, pressure measurements for those two hydrogeologic units were normalized taking into account variations in temperatures and fluid densities and then the calculated, or "observed", pressure heads were compared. The observed hydraulic head values were calculated using the HEADCO program (Spane and Mercer 1985) and represent the elevation of a water column for the static pressure/depth readings, and for the established formation fluid densities, and prevailing static fluid temperature/depth gradient at the stratigraphic well location (which varies between ~0.01 and 0.02°F/ft for respective depths). Figure 2.30 shows the calculated observed hydraulic head for the St. Peter and several selected Mount Simon pressure/depth measurements. The results indicate that there is a positive head difference in the Mount Simon that ranges from 47.8 to 61.6 ft above the calculated St. Peter observed static hydraulic head condition (i.e., 491.1 ft above MSL). This positive head difference suggests a natural vertical flow potential from the Mount Simon to the overlying St. Peter if hydraulic communication is afforded (e.g., an open communicative well). It should also be noted, however, that the higher head within the unconsolidated Quaternary aquifer (~611 ft above MSL), indicates a downward vertical flow potential from this surficial aquifer to both underlying St. Peter and Mount Simon bedrock aquifers (Figure 2.30).

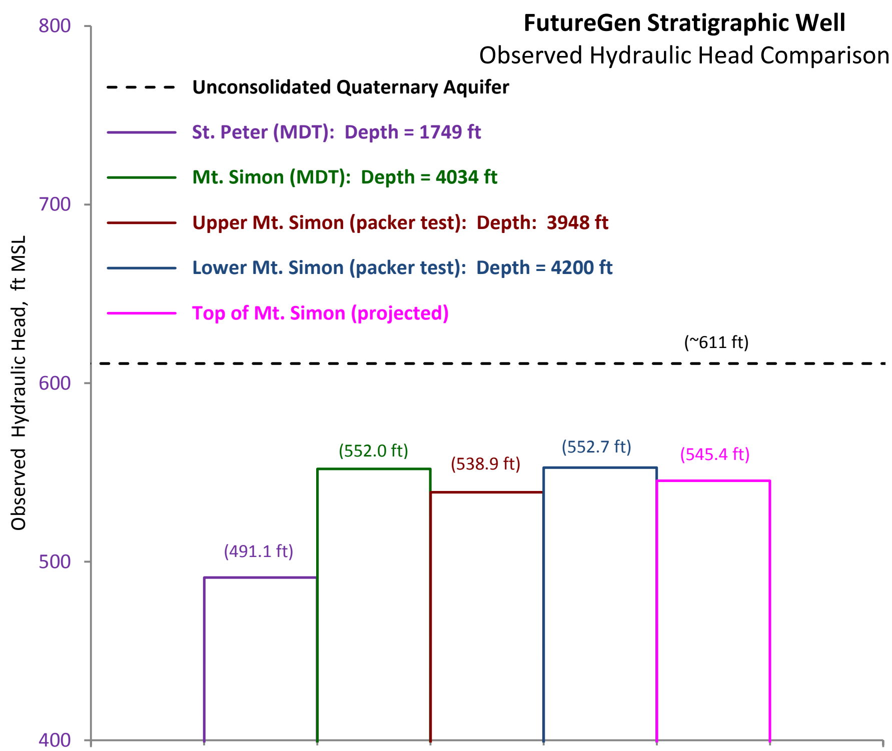

Figure 2.30. Observed Hydraulic Head Comparison Between the Unconsolidated Quaternary Aquifer, St. Peter Sandstone, and Mount Simon Sandstone Within the FutureGen Stratigraphic Well

The disparity in the calculated hydraulic head measurements (together with the significant differences in formation fluid salinity) also suggests that groundwater within the St. Peter and Mount Simon bedrock aquifers is physically isolated from one another. This is an indication that there are no significant conduits (open well bores or fracturing) between these two formations and that the Eau Claire forms an effective confining layer. Because the naturally occurring hydraulic head conditions are higher in the Mount Simon than the hydraulic heads in the St. Peter Formation, which is the lowest most USDW, the standard EPA methodology for determining the AoR pressure front is negated. However, it should also be noted that the upper unconsolidated Quaternary aquifer has a naturally higher hydraulic head than the Mount Simon. In addition, as indicated in Figure 2.30, all the bedrock aquifers, including the Mount Simon, have hydraulic heads lower than the upper unconsolidated Quaternary aquifer, which is the current source of drinking water for the area surrounding the FutureGen site. A discussion of the AoR determination is provided in Section 3.1.9 and a comprehensive monitoring plan that is protective of the USDW is presented in Chapter 5.0.

2.7 Site Evaluation of Mineral Resources

Other subsurface geochemical considerations include the potential for mineral or hydrocarbon resources beneath the proposed CO_2 storage site. While no significant mineral deposits are known to exist within Morgan County, natural gas has been recovered in the region, including at the Prentice and Jacksonville fields located within several miles of the stratigraphic well (Figure 2.31). ISGS oil and gas website data indicate that the Prentice Field contained more than 25 wells drilled during the 1950s; re-exploration occurred in the 1980s.[1] Both oil and gas have been produced from small stratigraphic traps in the shallow Pennsylvanian targets, at depths of 250 to 350 ft (75 to 105 m) bgs. It is important to note that gas produced from these wells may contain around 16 percent CO_2 (Meents 1981).

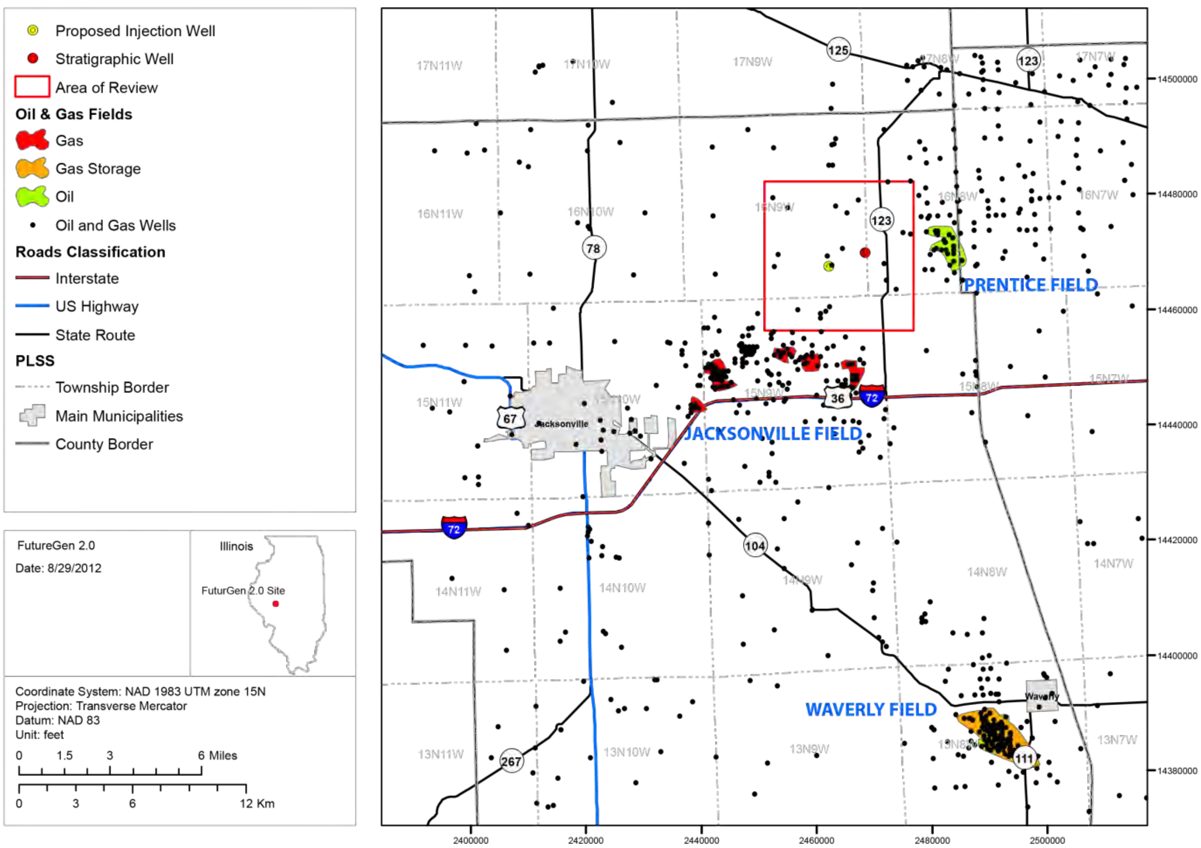

Figure 2.31. Map of Oil and Gas Wells Located Near the Proposed Morgan County CO_2 Storage Site (based on data from ISGS 2011a)

More than 75 wells have been drilled in the Jacksonville Field. Gas was discovered in the Jacksonville Field as early as 1890 (Bell 1927), but most oil and gas production from the Prentice and Jacksonville fields occurred between the late 1920s and late 1980s. The most productive formations in the Illinois Basin (lower Pennsylvanian and Mississippian siliciclastics and Silurian reefs) are not present in Morgan County. Only two boreholes in the vicinity of the Prentice Field and five boreholes near the Jacksonville Field penetrate through the New Albany Shale into Devonian and Silurian limestones.

[1] http://moulin.isgs.uiuc.edu/ILOIL/webapp/ILOIL.html, accessed on September 20, 2011.

Cumulative production from the Prentice and Jacksonville fields is not available, and both fields are largely abandoned. The Waverly Storage Field natural-gas storage site in the southeast corner of Morgan County originally produced oil from Silurian carbonates. This field no longer actively produces oil, but since 1954 it has been successfully used for natural-gas storage in the St. Peter and the Galesville/Ironton Sandstone formations (Buschbach and Bond 1974).

The nearest active coal mine is approximately 10 mi (16 km) away in Menard County and does not penetrate more than 200 ft (61 m) bgs (ISGS 2012a). A review of the known coal geology within a 5-mi (8-km) radius of the proposed drilling site indicates that the Pennsylvanian coals, the Herrin, Springfield, and Colchester coals, are very thin or are absent from the project area (ISGS 2010, 2011; Hatch and Affolter 2008). During continuous coring of a shallow groundwater monitoring well, immediately adjacent to the stratigraphic well, only a single thin (5-ft [1.5-m]) coal seam was encountered at about 200 ft (61 m) deep.

2.8 Wells Within the Survey Area

A survey area of 25 mi^2 (65 km^2) that is centered on the proposed injection location and encompasses the area of the expected CO_2 plume (the AoR) is shown in Figure 2.32. Surface bodies of water and other pertinent surface features (including structures intended for human occupancy), administrative boundaries, and roads are shown. There are no subsurface cleanup sites, mines, quarries, or Tribal lands within this area. Although numerous wells are located within a 25-mi^2 (65-km^2) survey area that includes the proposed injection location (Figure 2.32), none but the Alliance's stratigraphic well penetrates the injection zone (Mount Simon Sandstone and the lower Eau Claire [Elmhurst Sandstone Member]), the confining zone (Lombard and Proviso members of the Eau Claire Formation), or the secondary confining zone (Franconia Dolomite).

A total of 129 wells (including stratigraphic well) are within the survey area (see Appendix B); 51 wells are (or are potentially) within the AoR (Table 2.17). Indeed, 24 of these 51 water wells are only identified with a general location (center of a section) in the ISWS database. If the section of those wells intersected the AoR borders, the wells were assumed to be within the AoR even though they could be beyond the border. Those well are indicated with a "potentially" label in the last column of the Table 2.17 but are not shown on the map. Shallow domestic water wells with depths of less than 50 ft (15 m) are the most common well type. Five slightly deeper water wells were identified that range in depths from 110 ft (33 m) to 405 ft (123 m). Other wells include stratigraphic test holes, coal test holes, and oil and gas wells (Figure 2.32). Table 2.17 lists these wells with their unique API (American Petroleum Institute) identification number, ISWS well identification (ID), well location, depth, elevation, completion date, well owner, well type, and identified status.

The map in Figure 2.32 shows the locations of four proposed injection wells for which permits are being sought. It also shows the location of the Alliance's stratigraphic well and abandoned hydrocarbon test holes, coal test holes, oil and gas wells, other plugged and abandoned wells, known water wells, and other surface features within a 25-mi^2 (65-km^2) area centered on the location of the proposed injection wells. Figure 8.1 is a map of residences, water wells, and surface water features within the delineated AoR and survey area.

Table 2.17. List of Wells Located Within the AoR

Map ID	API Number	ISWS ID	Latitude NAD1983	Longitude NAD1983	Public Land Survey System	Total Depth ft	Elev ft	Completion Date	Owner	Well Num	Well Type	Status	Confining Zone Penetration Well	In AoR
0	121372213200		39.806064	-90.052919	T16n,R9w,Sec 25	4812	633	TBD	FutureGen Industrial Alliance, Inc.	1	Monitoring	Active	Yes	Yes
1	121372118200	116519	39.778074	-90.078443	T15N,R9W,Sec 2	25		19780712	A.A. Negus Estate	1	Water	Private Water Well	No	Yes
4	121370018700	115778	39.811025	-90.065241	T16N,R9W,Sec 25	115			Beilschmidt, William H.		Water		No	Yes
8	121370028500	115740	39.800661	-90.078386	T16N,R9W,Sec 26	127		1950	Martin, L. E.	1	Water		No	Yes
9		115741	39.800661	-90.078386	T16N,R9W,Sec 26	127			Martin, L. E.		Water		No	Yes
10	121372128600	115779	39.801129	-90.07342	T16N,R9W,Sec 26	25		19781213	Martin, Marvin & Jean	1	Water	Private Water Well	No	Yes
14		115763	39.792894	-90.078875	T16N,R9W,Sec 35	28			E Clemons		Water		No	Yes
15		115764	39.792894	-90.078875	T16N,R9W,Sec 35	25			B Sister		Water		No	Yes
16		115765	39.792837	-90.060294	T16N,R9W,Sec 36	35			J M Dunlap		Water		No	Yes
17	121370051100		39.792893	-90.078984	T16N,R9W,Sec 35	1056	643		O'Rear, Judge	1	Oil & Gas / Water		No	Yes
18	121370009900		39.808545	-90.06614	T16N,R9W,Sec 25	1530	630	19391001	Beilschmidt, Wm.	1	Oil & Gas	Dry and Abandoned, No Shows	No	Yes
19	121370023500		39.779153	-90.077325	T15N,R9W,Sec 2	338	644	19231101	Conklin	1	Oil & Gas	Dry and Abandoned, No Shows	No	Yes
20	121370023600		39.781298	-90.075082	T15N,R9W,Sec 2	348	646	19231101	Conklin	2	Oil & Gas	Dry and Abandoned, No Shows	No	Yes
21	121370023700		39.778057	-90.080754	T15N,R9W,Sec 3	342	645	19231001	Harris, A. J.	1	Oil & Gas	Gas Producer	No	Yes
22	121370023900		39.7779	-90.080756	T15N,R9W,Sec 3	334	644	19231107	Harris, A. J.	3	Oil & Gas	Gas Producer	No	Yes
25	121370036300		39.805251	-90.075597	T16N,R9W,Sec 26	1205		19670330	Martin	1	Oil & Gas	Dry and Abandoned, No Shows	No	Yes
26	121370036301		39.805251	-90.075597	T16N,R9W,Sec 26	1400		19731029	Martin	1	Oil & Gas	Junked and Abandoned, Plugged	No	Yes
27	121372088500		39.800861	-90.073017	T16N,R9W,Sec 26	302	630				Coal Test		No	Yes
		115735	39.807386	-90.060378	T16N,R9W,Sec 25	27			Beilschmidt, William H.		Water		No	Potentially
		115736	39.807386	-90.060378	T16N,R9W,Sec 25	30			W R Fowler		Water		No	Potentially
		115737	39.807386	-90.060378	T16N,R9W,Sec 25	28			Mason		Water		No	Potentially
		115739	39.807478	-90.079049	T16N,R9W,Sec 26	25			C H Matin		Water		No	Potentially
		115738	39.807478	-90.079049	T16N,R9W,Sec 26	22			T Gondall		Water		No	Potentially
		115650	39.807193	-90.041413	T16N,R8W,Sec 30	19		1930	R Allison		Water		No	Potentially
		115651	39.792765	-90.041512	T16N,R8W,Sec 31	28			W J Huston		Water		No	Potentially
		115652	39.792765	-90.041512	T16N,R8W,Sec 31	28			E Robinson		Water		No	Potentially
		116450	39.777005	-90.052023	T15N,R9W,Sec 1	25			A Harris		Water		No	Potentially
		116453	39.776968	-90.070521	T15N,R9W,Sec 2	32			A Harris		Water		No	Potentially
		116451	39.776968	-90.070521	T15N,R9W,Sec 2	22			W R Conklin		Water		No	Potentially
		116452	39.776968	-90.070521	T15N,R9W,Sec 2	30			B Negus		Water		No	Potentially
		116454	39.77688	-90.088996	T15N,R9W,Sec 3	28			C Negus		Water		No	Potentially
		116455	39.77688	-90.088996	T15N,R9W,Sec 3	30			L B Trotter		Water		No	Potentially
		115727	39.821881	-90.078925	T16N,R9W,Sec 23	30			D Flinn		Water		No	Potentially
		115728	39.821881	-90.078925	T16N,R9W,Sec 23	30			Hazel Dell School		Water		No	Potentially
		115729	39.821881	-90.078925	T16N,R9W,Sec 23	35			K Haneline		Water		No	Potentially
		115733	39.821811	-90.060168	T16N,R9W,Sec 24	30			J L Icenagle		Water		No	Potentially
		115734	39.821811	-90.060168	T16N,R9W,Sec 24	30			G Lewis		Water		No	Potentially
		115775	39.821811	-90.060168	T16N,R9W,Sec 24	200		1944	E C Lewis		Water		No	Potentially
		115742	39.807531	-90.097566	T16N,R9W,Sec 27	23			J Stewart		Water		No	Potentially
		115743	39.807531	-90.097566	T16N,R9W,Sec 27	23			I J Stewart		Water		No	Potentially
		115761	39.792917	-90.097513	T16N,R9W,Sec 34	28			T Harrison		Water		No	Potentially
		115762	39.792917	-90.097513	T16N,R9W,Sec 34	30			J Mahon		Water		No	Potentially

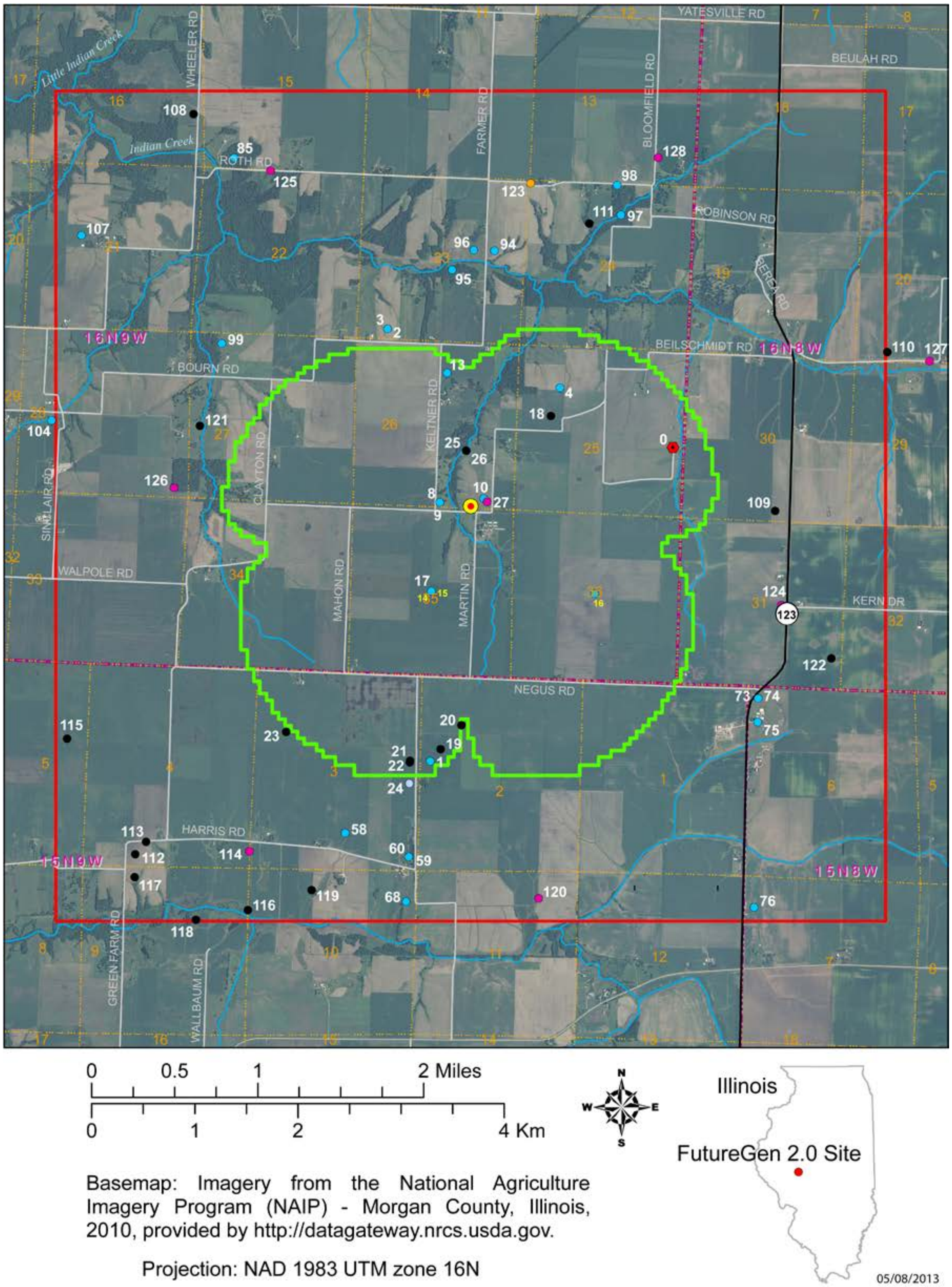

Figure 2.32. Wells Located Within the Survey Area. The map includes surface bodies of water, mines, quarries, faults, and other surface features. Tables of the data used to produce this map are provided in Table 2.17 and Appendix B.

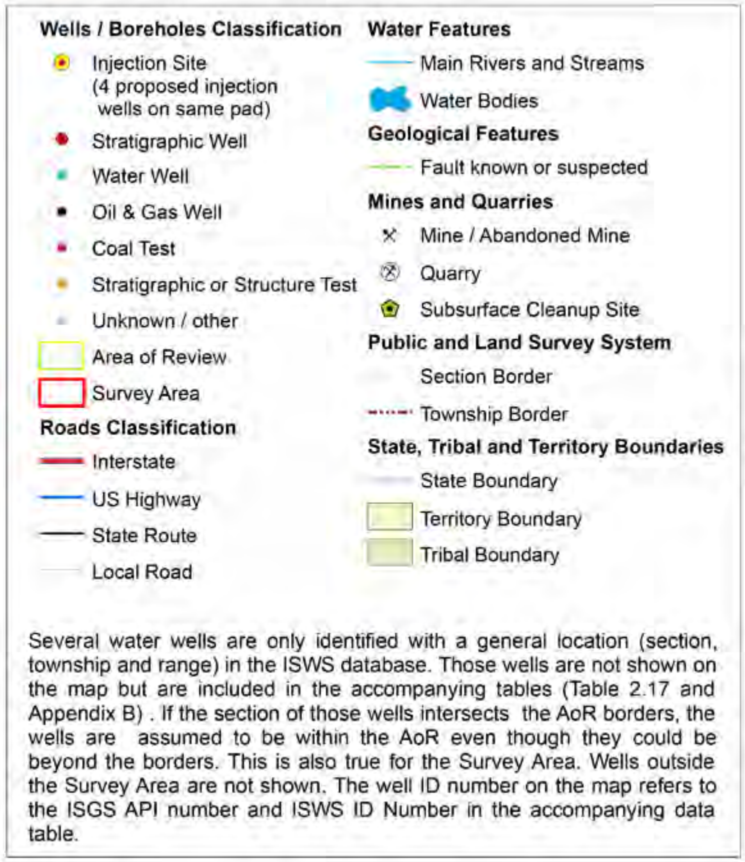

Figure 2.32. (contd)

2.9 Conclusion

The geologic setting of the proposed site indicates that the Mount Simon Sandstone at the site is sufficiently deep, and has sufficient thickness, lateral continuity, porosity, and permeability to store the proposed 22-MMT volume of CO_2. In addition, the Eau Claire Formation at the site is of sufficient thickness, lateral continuity, and has low enough permeabilities to serve as the primary confining zone. The site affords additional containment with several secondary confining zones, including the Franconian Formation. The basement rock was encountered at 4,430 ft and is a rhyolite, which will act as an impermeable lower boundary for the injection zones within the Mount Simon Sandstone. No potential conduits for CO_2 to migrate out of the Mount Simon reservoir were identified at the proposed storage site. Three relatively deep wells are present within the AoR, but none of them penetrates beyond the Maquoketa Shale which is significantly shallower than the primary confining zone. No faults or fractures were identified based on geophysical well logs of the stratigraphic well and from seismic analysis of the site. The rarity of tectonic fractures and lack of large-aperture tension fractures in the stratigraphic well, as determined from the image and sonic logs, indicate that the well is not proximal to normal (tensional) faults that might be close to failure.

Chapter 3.0 uses a conceptual model developed using the appropriate physical and chemical properties determined for the site to simulate the injection of 22 MMT of CO_2 over 20 years using a computational model. The physical and chemical input parameters for the computational model are described in more detail in Chapter 3.0.

2.10 References

40 CFR 144.3. Code of Federal Regulations, Title 40, Protection of the Environment, Part 144, "Underground Injection Control Program," Section 3, "Definitions."

40 CFR 146.82. Code of Federal Regulations, Title 40, *Protection of Environment*, Part 146, "Underground Injection Control Program: Criteria and Standards," Section 82, "Required Class VI permit information."

40 CFR 146.83(a). Code of Federal Regulations, Title 40, *Protection of Environment*, Part 146, "Underground Injection Control Program: Criteria and Standards," Section 83, "Minimum criteria for siting."

40 CFR 146.88. Code of Federal Regulations, Title 40, Protection of Environment, Part 146"Underground Injection Control Program: Criteria and Standards," Section 88, "Injection well operating requirements."

Bell AH. 1927. *Recent Developments in the Vicinity of Jacksonville*. Illinois Petroleum Report 11, Illinois State Geologic Survey, Urbana, Illinois.

Bergstrom RE and AJ Zeizel. 1957. *Groundwater Geology in Western Illinois, South Part*. Circular 232, Illinois State Geological Survey, Urbana, Illinois.

Bethke CM and S Marshak. 1990. "Brine Migrations across North America − The Plate Tectonics of Groundwater." *Annual Review Earth and Planetary Sciences*, 18, 287–315. (Reprinted in WE Dietrich and G Sposito, eds., (1997) *Hydrologic Processes from Catchment to Continental Scales*, Annual Reviews, Inc.)

Bickford ME, WR Van Schmus, and I Zietz. 1986. "Proterozoic history of the midcontinent region of North America." *Geology* 14(6):492–496.

Birkholzer JT, Q Zhou, J Rutqvist, P Jordan, K Zhang, and CF Tsang. 2007. *Research Project on CO_2 Geological Storage and Groundwater Resources: Large-Scale Hydrogeological Evaluation and Impact on Groundwater Systems, Annual Report: October 1, 2006 to September 30, 2007.* LBNL-63544, Lawrence Berkeley National Laboratory, Berkeley, California.

Birkholzer JT, Q Zhou, K Zhang, P Jordan, J Rutqvist, and CF Tsang. 2008. *Research Project on CO_2 Geological Storage and Groundwater Resources Large-Scale Hydrological Evaluation and Modeling of the Impact on Groundwater Systems Annual Report: October 1, 2007, to September 30, 200*8. Lawrence Berkeley National Laboratory, Berkeley, California.

Bowen BB, R Ochoa, ND Wilkens, J Brophy, TR Lovell, N Fischietto, C Medina, and J Rupp. 2011. "Depositional and Diagenetic Variability Within the Cambrian Mount Simon Sandstone: Implications for Carbon Dioxide Sequestration." *Environmental Geosciences* 18:69-89.

Buschbach TC and DC Bond. 1974. *Underground Storage of Natural Gas in Illinois − 1973*. Illinois Petroleum 101, Illinois State Geological Survey, Champaign, Illinois.

Buschbach TC and DR Kolata. 1991. "Regional Setting of Illinois Basin." *In* Leighton MW, Kolata DR, Oltz DF, and Eidel JJ (eds.), *Interior Cratonic Basins*. *American Association of Petroleum Geologists Memoir* 51:29–55.

Daniels DL, RP Kucks, and PL Hill. 2008. Illinois, Indiana, and Ohio Magnetic and Gravity Maps and Data: A Website for Distribution of Data. U.S. Geological Survey Data Series 321. Available at: http://pubs.usgs.gov/ds/321/.

Dey WS, RA Locke, IG Krapac, CG Patterson, and JL Hurry. In press. *Preliminary Hydrogeologic Investigation of the FutureGen 2 Site in Morgan County, Illinois*. Prepared by the Illinois State Geological Survey for Pacific Northwest National Laboratory, Richland, Washington.

Driese SG, CW Byers, and RH Dott. 1981. "Tidal deposition in the basal upper Cambrian Mount Simon Formation in Wisconsin." *Journal of Sedimentary Research* 51:367-381.

EPA (U.S. Environmental Protection Agency). 2011. *Underground Injection Control Permit Application IL-ICCS Project*. Submitted to the EPA Region 5 by Archer Daniels Midland Company, Decatur, Illinois.

EPA (U.S. Environmental Protection Agency). 1994. *Determination of Maximum Injection Pressure for Class I Wells*. Underground Injection Control Section Regional Guidance #7. EPA Region 5, Chicago, Illinois.

Freiburg T and HE Leetaru. 2012. "Controls on Porosity Development and the Potential for CO_2 Sequestration or Waste Water Disposal in the Cambrian Potosi Dolomite (Knox Group): Illinois Basin" (abstract) *AAPG Search and Discovery Article #90154.* AAPG 41st Annual Eastern Section Meeting, September 22-26, 2012, Cleveland, Ohio. http://www.searchanddiscovery.com/abstracts/html/2012/90154eastern/abstracts/freib.htm Accessed on August 15, 2012.

Gibb JP and M O'Hearn. 1980. *Illinois Ground Water Quality Data Summary*. Contract Report 230, Illinois State Water Survey, Urbana, Illinois.

Goetz LK, JG Tyler, RL Macarevich, D Brewster, and JR Sonnad. 1992. "Deep gas play probed along Rough Creek graben in Kentucky part of Illinois Basin." *Oil and Gas Journal* 90:97-101.

Gupta N and ES Bair. 1997. "Variable-Density Flow in the Midcontinent Basins and Arches Region of the United States." *Water Resources Research* 33:1785–1802.

Hanson GF. 1960. *Summary Statement of Facilities for Underground Storage of Liquid Petroleum Products in Wisconsin*. University of Wisconsin, Wisconsin Geological and Natural History Survey, Madison, Wisconsin.

Hatch JR and RH Affolter. 2008. "Geologic Overview." *In* Hatch JR and RH Affolter (eds.) Chapter C of *Resource Assessment of the Springfield, Herrin, Danville, and Baker Coals of the Illinois Basin*. U.S. Geological Survey Professional Paper 1625-D, Government Printing Office, Washington D.C.

Helmotz Centre Potsdam – GFZ. 2012. *World Stress Map Project*. Available at http://dc-app3-14.gfz-potsdam.de/. Last accessed on 5/9/2012.

Houseknecht DW. 2001. "Earliest Paleozoic stratigraphy and facies, Reelfoot Basin and adjacent craton." Pp. 27−44, in Gregg, JM, JR Palmer, and VE Krutz (eds.), *Field Guide to the Upper Cambrian of Southeastern Missouri: Stratigraphy, Sedimentology, and Economic Geology*. OFR-01-98-GS, Missouri Department of Natural Resources Open-file Report, Rolla, Missouri.

Hunt LI. 2004. *A Petrophysical and Shallow Geophysical Study to Determine Pathways of Gas Migration Within and Above an Underground Gas Storage Field in North-Central Illinois*. Illinois State University, Normal, Illinois.

IDNR (Iowa Department of Natural Resources). 2012. Iowa Geological and Water Survey GeoSam Database website. Available at: http://www.igsb.uiowa.edu/webapps/geosam/.

ISGS (Illinois State Geological Survey). 2012a. Coal Mines, Coal Geology, and Resource Data Online, County Coal Map and Data Series, Morgan County. Available at: http://www.isgs.uiuc.edu/maps-data-pub/coal-maps/counties/morgan.shtml. Last accessed January 4, 2012.

ISGS (Illinois State Geological Survey). 2012b. Illinois Natural Resources Geospatial Data Clearinghouse, Glacial Drift Thickness and Character map revised in 1998. Available at: http://www.isgs.uiuc.edu/nsdihome/

ISGS (Illinois State Geological Survey). 2012c. ILWATER Interactive Mapping Web Interface. Available at: http://www.isgs.illinois.edu/maps-data-pub/wwdb/launchims.shtml. Last accessed on January 4, 2012.

ISGS (Illinois State Geological Survey). 2012d. Surficial Geology and Features Quaternary Deposits Map website. Available at: http://www.isgs.uiuc.edu/sections/quat/deposit-map.shtml. Last accessed on February 14, 2012.

ISGS (Illinois State Geological Survey). 2011. Illinois Oil and Gas Resources (ILOIL) Internet Map Service, http://moulin.isgs.uiuc.edu/ILOIL/webapp/ILOIL.html. Last accessed on October 8, 2011.

Kisvarsanyi EB. 1979. *Geologic Map of the Precambrian* of *Missouri.* Contributions to Precambrian Geology No 7, 1:1000000 map, Missouri Department of Natural Resources, Jefferson City, Missouri.

Kolata DR. 2005. Bedrock Geology of Illinois. Illinois Map 14 1:500,000, Illinois State Geological Surve, Urbana, Illinois.

Kolata DR and J Nelson. 1991. "Tectonic History of the Illinois Basin." Pp. 263−285 in MW Leighton, DR Kolata, DF Oltz, and JJ Eidel (eds.), Interior Cratonic Basins. *Memoir 51, American Association of Petroleum Geologists*. Tulsa, Oklahoma.

Kolata DR and CK Nimz. 2010. *Geology of Illinois*. Illinois State Geologic Survey, Urbana, Illinois.

Leetaru HE and JH McBride. 2009. "Reservoir uncertainty, Precambrian topography, and carbon sequestration in the Mt. Simon Sandstone, Illinois Basin." *Environmental Geosciences* 16(4):235-243.

Leetaru HE, DG Morse, R Bauer, SM Frailey, D Keefer, DR Kolata, C Korose, E Mehnert, S Rittenhouse, J Drahovzal, S Fisher, JH McBride. 2005. "Saline reservoirs as a sequestration target." In *An Assessment of Geological Carbon Sequestration Options in the Illinois Basin*, Final Report for U.S. DOE Contract: DE-FC26-03NT41994, Principal Investigator: Robert Finley. Midwest Geological Sequestration Consortium, Champaign, Illinois.

Leetaru HE, SM Frailey, D Morse, RJ Finley, JA Rupp, JA Drahozval, and JH McBride. 2009. "Carbon sequestration in the Mount Simon Sandstone saline reservoir." *In* Grobe M, JC Pashin, and RL Dodge (eds.), Carbon dioxide sequestration in geological media—State of the science, *AAPG Studies in Geology* 59:261-277.

Lidiak EG. 1996. "Geochemistry of subsurface Proterozoic rocks in the eastern Midcontinent of the United States: Further evidence for a within-plate tectonic setting." Pp. 45-66, in van der Pluijm BA and Catacosinos PA (eds.), *Basement and Basins of Eastern North America*. Special Paper 308, Geological Society of America, Boulder, Colorado.

Lloyd OB and WL Lyke. 1995. *Ground Water Atlas of the United States*, Segment 10. United States Geological Survey, U.S. Government Printing Office, Washington D.C.

McBride JH and DR Kolata. 1999. "Upper Crust Beneath Central Illinois Basin, United States". *GSA Bulletin* 111(3)375-394.

MDNR (Missouri Department of Natural Resources). 2012. Missouri Department of Natural Resources Water Resources Center, Geologic Well Logs of Missouri website. Available at: http://www.dnr.mo.gov/env/wrc/logmain/index.html.

Meents WF. 1981. *Analysis of Natural Gas in Illinois, Gas, Natural – Illinois*. Illinois State Geological Survey, Urbana, Illinois.

Morse DG and HE Leetaru. 2005. *Reservoir characterization and three-dimensional models of Mt. Simon Gas Storage Fields in the Illinois Basin*. Circular 567, Illinois State Geological Survey, Urbana, Illinois (CD-ROM).

Nelson WJ. 1995. *Structural Features in Illinois*. Bulletin 100, Illinois State Geological Survey, Champaign, Illinois.

Saller AH, J Schwab, S Walden,S Robertson, R Nims, H Hagiwara, and S Mizohata. 2004. "Three-dimensional seismic imaging and reservoir modeling of an upper Paleozoic "reefal" buildup, Reinecke Field, west Texas, United States." Pp. 107-125 in GP Eberli, JL Masaferro, and JF Sarg (eds.), *Seismic Imaging of Carbonate Reservoirs and Systems*, Volume 81, American Association of Petroleum Engineers, Tulsa, Oklahoma.

Sargent ML and Z Lasemi. 1993. "Tidally dominated depositional environment for the Mount Simon Sandstone in central Illinois." *Great Lakes Section, Geological Society of America, Abstracts and Programs* 25(3):78.

Selkregg LF and JP Kempton. 1958. *Groundwater Geology in East-Central Illinois.* Circular 248, Illinois State Geological Survey, Urbana, Illinois.

Sminchak J. 2011. *Conceptual Model Summary Report Simulation Framework for Regional Geologic CO_2 Storage Along Arches Province of Midwestern United States*, Topical Report. Battelle Memorial Institute, Columbus, Ohio.

Spane FA and RB Mercer. 1985. *HEADCO: A Program for Converting Observed Water Levels and Pressure Measurements to Formation Pressure and Standard Hydraulic Head*. RHO-BW-ST-71P, Rockwell Hanford Operations, Richland, Washington.

Streit JE and RR Hillis. 2004. "Estimating Fault Stability and Sustainable Fluid Pressures for Underground Storage of CO_2 in Porous Rock." *Energy* 29(9-10):1445-1456.

USGS (U.S. Geological Survey). 2012a. Illinois – Earthquake History. Available at: http://earthquake.usgs.gov/earthquakes/states/illinois/history.php. Last accessed August 29, 2012

USGS (U.S. Geological Survey). 2012b Earthquake Search. Available at: http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_circ.php. Last accessed on August, 29, 2012.

USGS (U.S Geological Survey). 2008. National Seismic Hazard Mapping Project, Earthquake Hazards Program. Last accessed on September 24, 2012 at http://earthquake.usgs.gov/hazards/.

Weiss WW, X Xie, and JW Weiss. 2009. "Field Test of Wettability Alteration to Increase the Flow Rate from Aquifer Gas Storage Wells." Paper 12567, SPE Eastern Regional Meeting, 23-25 September 2009, Charleston, West Virginia. ISBN 978-1-55563-262-5. Available at: http://www.onepetro.org/mslib/servlet/onepetropreview?id=SPE-125867-MS.

Whiting LL and DL Stevenson. 1965. *The Sangamon Arch*. Circular 383, Illinois State Geological Survey, Urbana, Illinois.

Wilkens ND, N Fischietto, BB Bowen, and J Rupp. 2011. "Anatomy of a Cambrian Sheet Sand: Depositional Environments in the Mount Simon Sandstone." *GSA Abstracts with Programs* 42(5), Geological Society of America, Boulder, Colorado.

Willman HB, E Atherton, TC Buschbach, C Collinson, JC Frey, ME Hopkins, JA Lineback, and JA Simon. 1975. *Handbook of Illinois Stratigraphy*. Bulletin 95, Illinois State Geological Survey, Urbana, Illinois.

Woller DM and EW Sanderson. 1979. "Public Groundwater Supplies in Morgan and Scott Counties." Bulletin 60-27, Illinois State Water Survey, Illinois Institute of Natural Resources, Urbana, Illinois.Young HL. 1992. "Hydrogeology of the Cambrian-Ordovician aquifer system in the northern Midwest, United States." Professional Paper 1405-B, U.S. Geological Survey, U.S. Government Printing Office, Washington D.C.

Zhou Q, JT Birkholzer, E Mehnert, Y-F Lin, and K Zhang. 2010. "Modeling Basin- and Plume-Scale Processes of CO_2 Storage for Full-Scale Deployment." *Ground Water* 48(4):494-514.

Zoback MD, CA Barton, M Brudy, DA Castillo, T Finkbeiner, BR Grollimund, DB Moos, P Peska, CD Ward, and DJ Wiprut. 2003. "Determination of stress orientation and magnitude in deep wells." *International Journal of Rock Mechanics and Mining Sciences* 40(7–8):1049-1076.

Zoback MD. 2007. *Reservoir Geomechanics*, Cambridge University Press, Cambridge, England.