

# *Reservoir uncertainty, Precambrian topography, and carbon sequestration in the Mt. Simon Sandstone, Illinois Basin*

**Hannes E. Leetaru and John H. McBride**

## **ABSTRACT**

Sequestration sites are evaluated by studying the local geological structure and confirming the presence of both a reservoir facies and an impermeable seal not breached by significant faulting. The Cambrian Mt. Simon Sandstone is a blanket sandstone that underlies large parts of Midwest United States and is this region's most significant carbon sequestration reservoir. An assessment of the geological structure of any Mt. Simon sequestration site must also include knowledge of the paleotopography prior to deposition.

Understanding Precambrian paleotopography is critical in estimating reservoir thickness and quality. Regional outcrop and borehole mapping of the Mt. Simon in conjunction with mapping seismic reflection data can facilitate the prediction of basement highs. Any potential site must, at the minimum, have seismic reflection data, calibrated with drill-hole information, to evaluate the presence of Precambrian topography and alleviate some of the uncertainty surrounding the thickness or possible absence of the Mt. Simon at a particular sequestration site. The Mt. Simon is thought to commonly overlie Precambrian basement granitic or rhyolitic rocks. In places, at least about 549 m (1800 ft) of topographic relief on the top of the basement surface prior to Mt. Simon deposition was observed. The Mt. Simon reservoir sandstone is thin or not present where basement is topographically high, whereas the low areas can have thick Mt. Simon. The paleotopography on the basement and its correlation to Mt. Simon thickness have been observed at both outcrops and in the subsurface from the states of Illinois, Ohio, Wisconsin, and Missouri.

## **INTRODUCTION**

The Cambrian Mt. Simon Sandstone is a regional blanket sandstone that underlies large parts of Midwest United States and is the primary

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SYSTEM	GROUP	FORMATION
Ordovician	Maquoketa	Brainard
		Ft. Atkinson
		Scales
	Galena	Kimmswick
		Decorah
	Platteville	
	Ansell	Joachim
		St. Peter
	Praire du Chien	Shakoppee
		New Richmond
Oneota		
Gunter		
Cambrian	Knox	Eminence
		Potosi
		Franconia
		Ironton-Galesville
		Eau Claire
		Mt. Simon
Precambrian		

**Figure 1.** Stratigraphic column of Ordovician through Precambrian rocks in Illinois.

saline reservoir for carbon sequestration in the region. In the Illinois Basin, the Mt. Simon attains a maximum thickness of 792 m (2600 ft) in east-central Illinois and west-central Indiana and is an ideal target for sequestration (Leetaru et al., in press). The Eau Claire Formation, directly overlying the Mt. Simon, provides the primary seal that will prevent CO<sub>2</sub> migration into shallower formations (Figure 1). Note that numerous deep well penetrations never encountered the Mt. Simon or the Eau Clair Formation and instead drilled directly into granite basement. These areas of absent or thin Mt. Simon are predictable and can be identified by seismic reflection data.

Based on the existing well control, mapping of the Precambrian crystalline basement indicates that subsurface paleotopographic relief in the Illinois Basin ranges from 150 m (500 ft) to more than 427 m (1400 ft) (Sargent, 1991). Precambrian topographic relief has been described in Illinois, Ohio, Wisconsin, and Missouri (Workman and Bell, 1948; Dean and Baranoski, 2002; Reuter and Watts, 2004). In Missouri and Illinois, the basement topographic relief was high enough that neither the Mt. Simon nor the overlying Eau Claire Formation was ever deposited, and yet, within a short distance (a few kilometers or miles), the seal is again

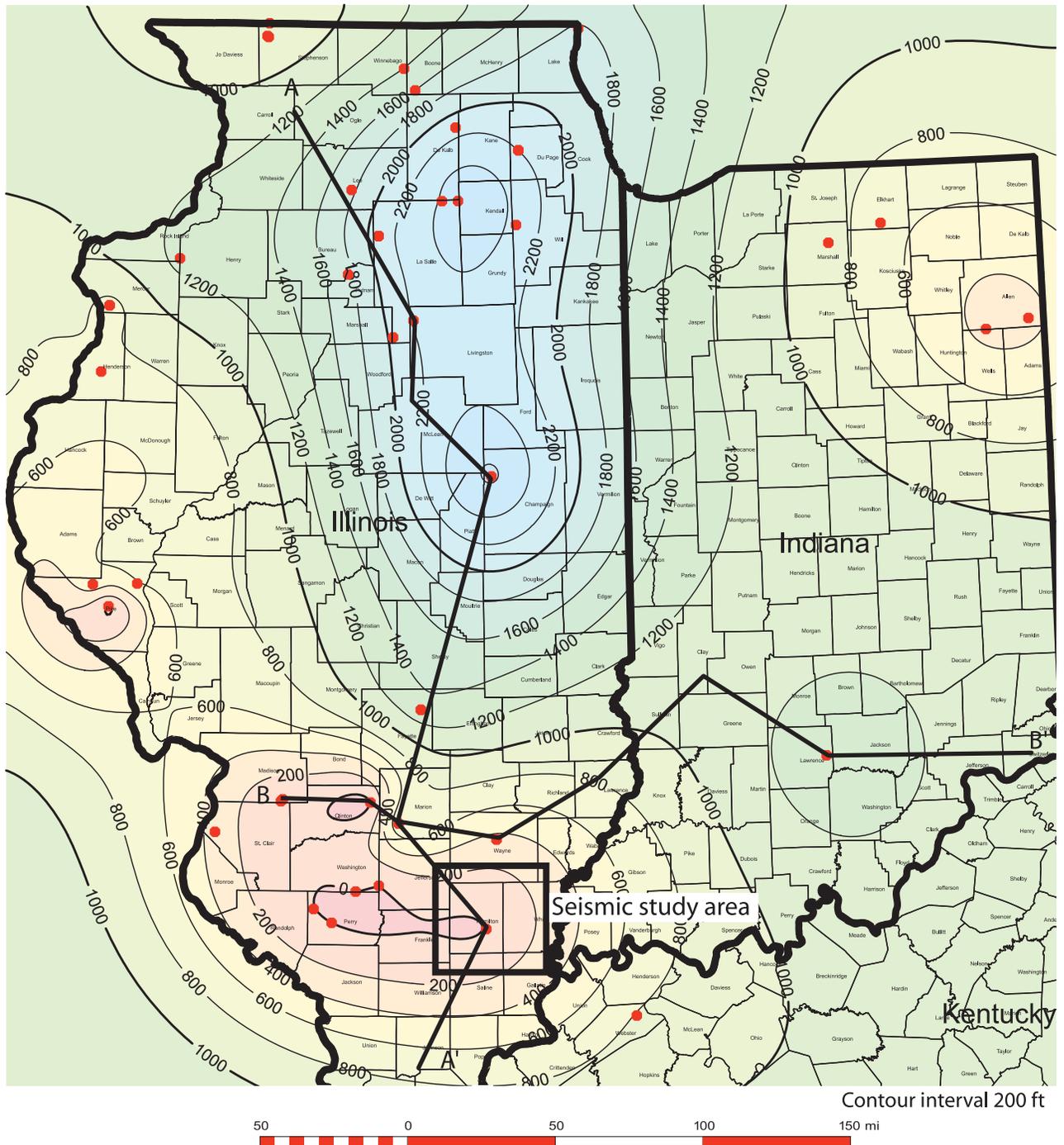
present and the Mt. Simon reservoir can be more than 305 m (1000 ft) thick. Therefore, the identification of these basement topographic highs is critical in decreasing our uncertainty of finding a sink and a seal for carbon sequestration. Rapid changes in basement relief can occur in most of the Illinois Basin, but the available well control suggests that the significant basement relief occurs where the Mt. Simon is thin or absent in the southern and western part of the study area.

The Mt. Simon Sandstone is estimated to be Upper Cambrian in age and lies unconformably on Precambrian basement rocks that are composed of granite, granodiorite, or rhyolite (Bradbury and Atherton, 1965; Atekwana, 1996). Much of the Precambrian basement formed between 1.48 and 1.38 billion years ago and is part of the eastern granite-rhyolite province (Bickford et al., 1986; Lidiak, 1996; Van Schmus et al., 1996). The Precambrian rocks occur at depths from 610 m (2000 ft) in the northernmost part of Illinois to more than 4300 m (14,000 ft) below the surface in the southern part of the Illinois Basin. The unconformity between the overlying Mt. Simon (also known as the sub-Sauk unconformity) is estimated to span 600 to 900 m.y. (Willman et al., 1975).

In east-central Illinois, the Mt. Simon may be resting on a Precambrian unit with up to 3600 m (12,000 ft) of rocks called the Centralia sequence (Pratt et al., 1992). On seismic reflection profiles, these sub-Mt. Simon strata display coherent reflectors suggestive of a sedimentary succession (McBride et al., 2003).

At its thickest point in the Illinois Basin, the Mt. Simon is more than 790 m (2600 ft) thick (Figure 2). The Mt. Simon does not crop out in Illinois, but correlative units are exposed in southern Wisconsin, southeastern Minnesota, and southeastern Missouri. In Missouri, the Mt. Simon is stratigraphically equivalent to the Lamotte Sandstone of Missouri (Workman and Bell, 1948; Houseknecht and Ethridge, 1978). The Mt. Simon may correlate to equivalents in the Bayfield Sandstone of northern Wisconsin, the Jacobsville Sandstone of northern Michigan, and the Fond du Lac Sandstone of Minnesota (Buschbach, 1964). The Mt. Simon comprises the lower part of the Sauk sequence of Sloss (1963). The regional relationships of the lower Sauk were summarized by Sargent (1991).

The north-central part of Illinois has the thickest Mt. Simon Sandstone, whereas the western and southern flanks of the Illinois Basin have a Mt. Simon that is either thin or not present (Figure 2). Most of the basement topographic highs have been found in those areas

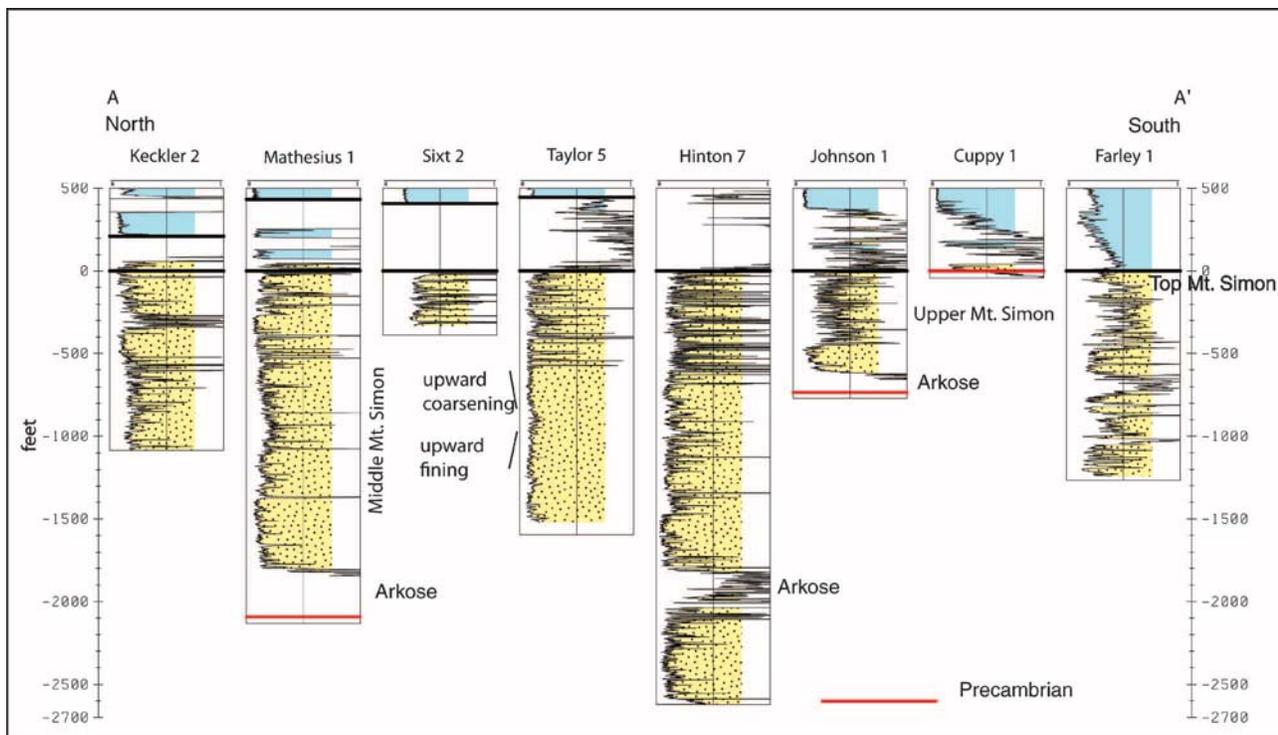


**Figure 2.** Thickness of the Mt. Simon Sandstone in the Illinois Basin. The locations of cross sections AA' and BB' are also shown. The seismic study area (black outline) is used to illustrate the potential of using seismic reflection data to locate Precambrian basement highs.

with regionally thin Mt. Simon. The topographic relief on top of the Precambrian granites has been observed in both outcrops and in the subsurface. The Canadian shield has been considered as the primary source of the Mt. Simon sediment. Paleocurrents flowed from the north and northeast of the Illinois Basin (Ojakangas,

1963). The Ozark dome at the St. Francois Mountains was a secondary source for these sandstones (Houseknecht and Ethridge, 1978).

Regional mapping in the central part of Illinois shows that the Cambrian Eau Claire is a persistent shale interval above the Mt. Simon that is expected to provide



**Figure 3.** North–south cross section of the Eau Claire and Mt. Simon across the Illinois Basin illustrating the stratigraphic relationships of these two units (datum is the top of the Mt. Simon Sandstone).

a good seal. The Eau Claire ranges from 91 m (300 ft) thick in the western and northern part of Illinois to more than 305 m (1000 ft) in the southern part of the basin. The Eau Claire Formation is composed primarily of a silty, argillaceous dolomitic sandstone or sandy dolomite in northern Illinois and becomes a siltstone or shale in the central part of the Illinois Basin (Willman et al., 1975). In the southern part of the basin, the Eau Claire is a mixture of dolomite and limestone with some fine-grained siliciclastics.

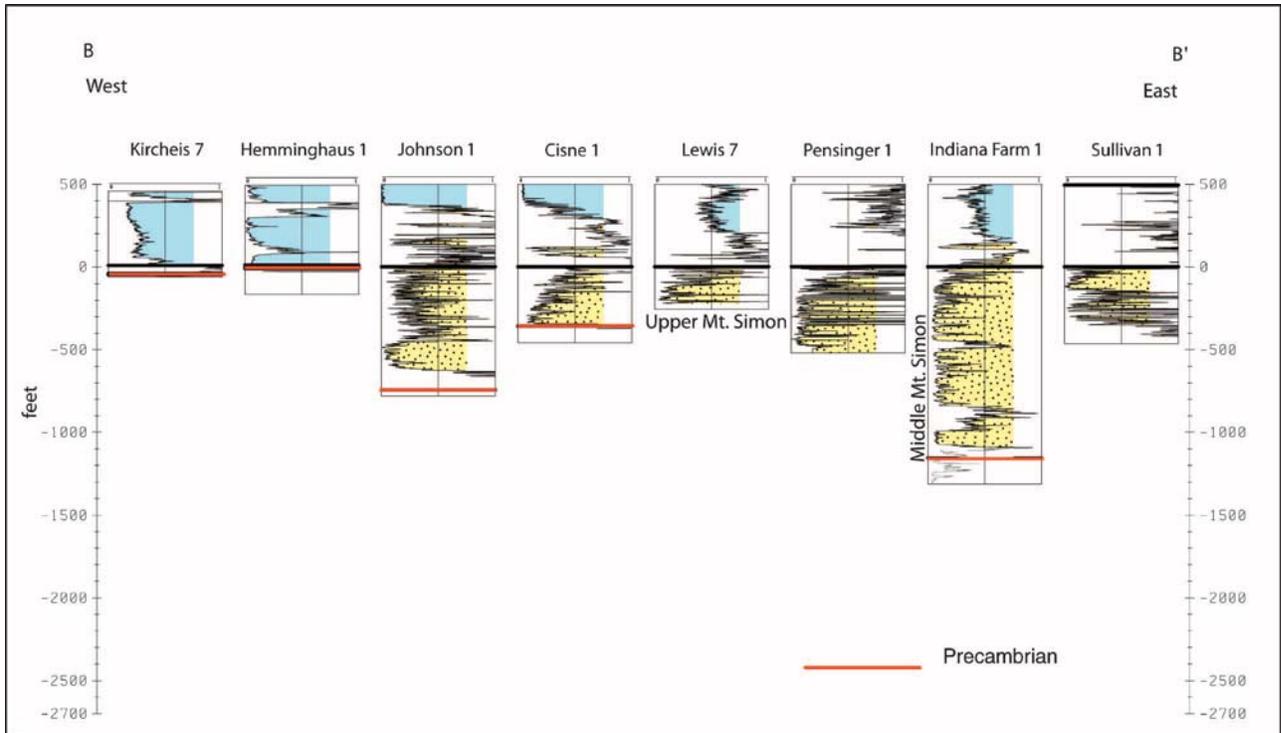
## CROSS SECTIONS

Regional cross sections (Figures 3, 4) over the Illinois Basin suggest that the Mt. Simon can be subdivided into three distinct electrofacies. Both the north–south (Figure 3) and east–west (Figure 4) cross sections have the Mt. Simon Sandstone as their datum. The gamma-ray log measures the amount of naturally occurring radioactivity in a formation. The finer grained sandstones commonly have more abundant clay minerals, which contain radioactive elements. The coarser grained rocks contain less feldspar and clay minerals. The gamma-ray

log data have been normalized to the lowest log value, which is taken to represent a sandstone. A linear relation is then assumed between normalized log response and grain size, which would be appropriate for older, well-consolidated sedimentary rocks. The normalized gamma-ray (shale volume or  $V_{shale}$ ) curve is used to infer grain size. (In some cases, especially for older, well-consolidated rocks, it is appropriate to assume that the shale index [ $I_{shale}$ ] is equivalent to  $V_{shale}$ ).

The uppermost Mt. Simon Sandstone electrofacies unit (Figure 3) is composed of thin (3.0–6.1 m [10–20 ft]) sandstone beds that are interbedded with thin (<0.3 m [1 ft]) shale and siltstone beds. The uppermost Mt. Simon unit is used for natural gas storage in the northern part of Illinois. Interpretation of core through this upper Mt. Simon section suggests a nearshore, tidally influenced depositional system (Morse and Leetaru, 2005).

The middle Mt. Simon electrofacies unit has thicker sandstone beds than the upper unit. It also has a central finer grained interval with coarsening both upward and downward. This electrofacies can best be observed on the north–south cross section where the Mt. Simon is the thickest (Figure 3). No core from this interval exists, and it does not appear to be correlative to facies on the



**Figure 4.** East–west cross section of the Eau Claire and Mt. Simon across the Illinois Basin illustrating the stratigraphic relationship of these two units (datum is the top of the Mt. Simon Sandstone).

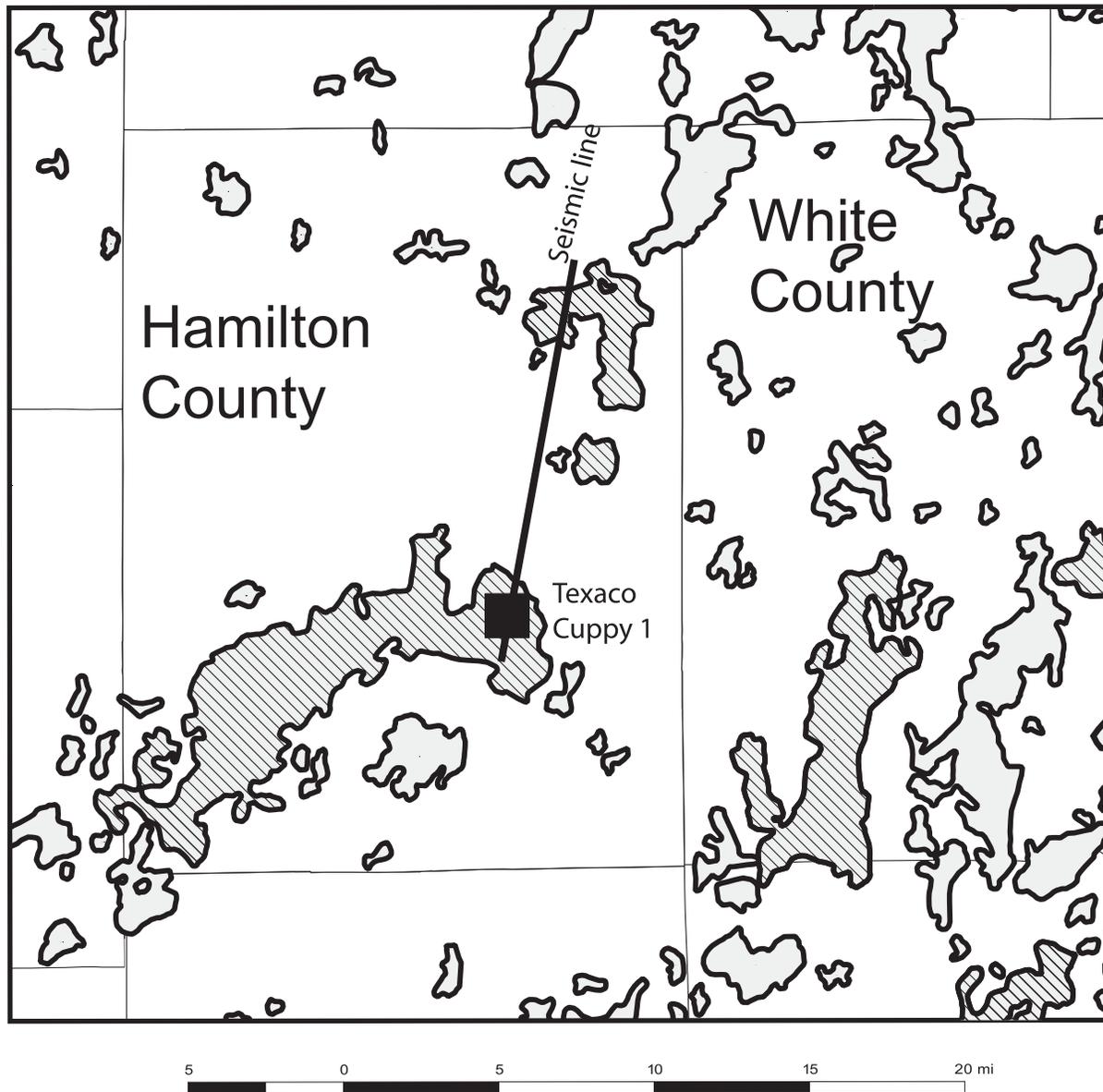
outcrop belt; therefore, no potential depositional environment can be given.

The lowermost Mt. Simon electrofacies unit has thick-bedded sandstone with some beds being greater than or equal to 30 m ( $\geq 100$  ft) in thickness (Figure 3). Arkosic intervals with a high gamma-ray response are also observed, which have permeabilities of more than 1 d and porosities that average more than 20% (Leetaru et al., in press). These arkosic intervals appear to be widespread near the base of the Mt. Simon and are observed in both outcrop and subsurface data.

The east–west cross section (Figure 4) illustrates some of the problems of studying the Mt. Simon Sandstone. Most of the wells penetrate only the upper 61 m (200 ft) of Mt. Simon and did not encounter the middle and lower Mt. Simon facies. The two western wells in the cross sections did not penetrate Mt. Simon and instead drilled through a thin Eau Claire Formation into granite. The features on which these wells were drilled were topographically high during the Eau Claire and Mt. Simon deposition. The Bonneterre Dolomite (Eau Claire Formation) in Missouri contains igneous rock fragments, suggesting that Precambrian paleohigh areas were present that were islands during the deposition of these carbonates (Houseknecht and Ethridge, 1978).

## IDENTIFICATION OF BASEMENT HIGHS

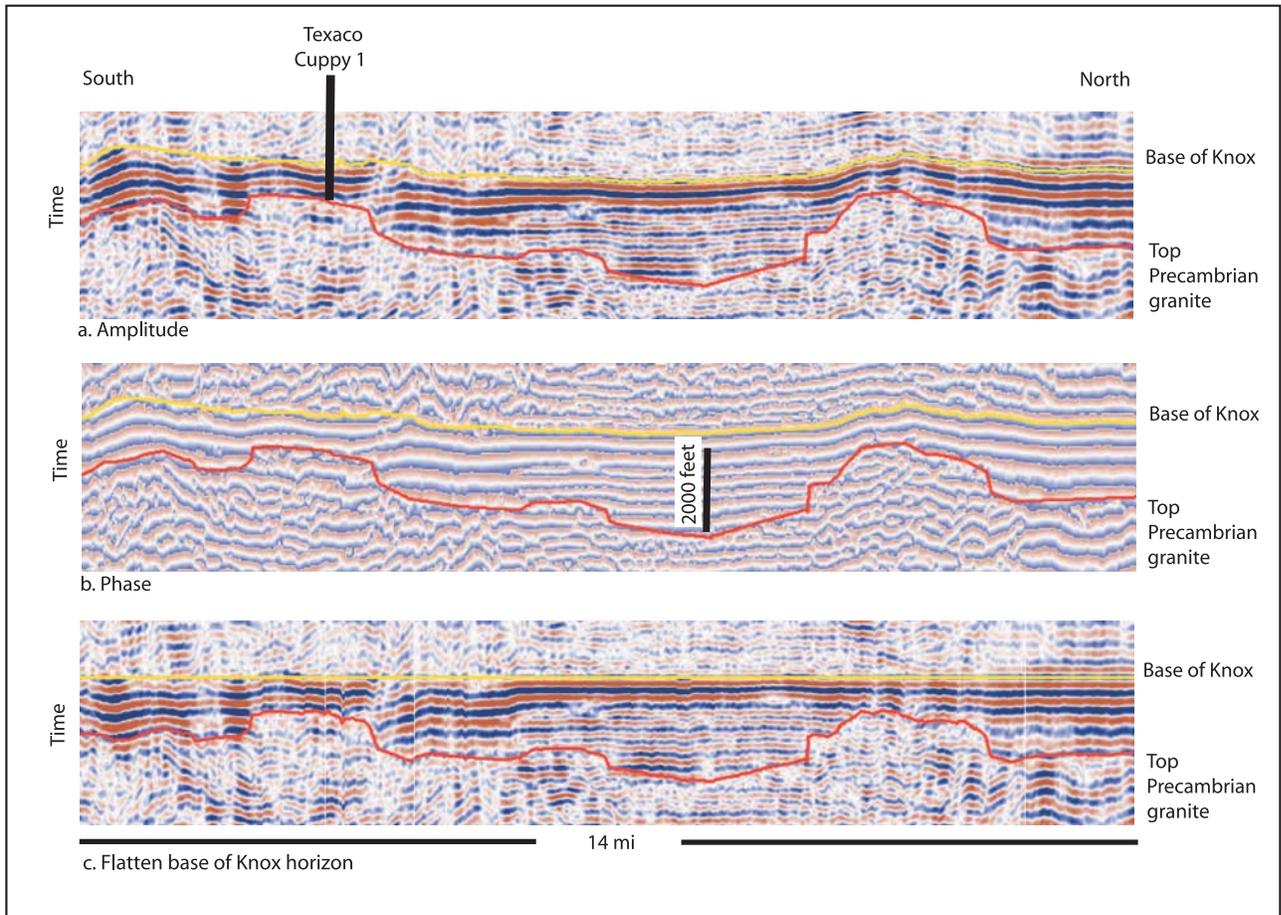
Mapping from seismic reflection data may be the only way to identify these Precambrian basement highs before actually drilling a well. For this study, we use an area in southeastern Illinois (Hamilton and White Counties) as an example (Figures 2, 5) because the Mt. Simon is thin here and a deep drill hole (Texaco Cuppy) penetrated a Precambrian high with no Mt. Simon and encountered granite at a depth of 3966 m (13,014 ft) (Figure 3) (Potter et al., 1997). Previous research has shown that wells penetrating Mt. Simon at depths greater than 3000 m (10,000 ft) have not encountered reservoir-quality porosity and permeability; therefore, the Mt. Simon in this area is probably too deep for carbon sequestration (Leetaru et al., in press). In the study area, the Eau Claire is composed of shales and carbonate strata. A north–south seismic profile (Figure 6) across the study area shows the relief on the Precambrian basement with the well on a prominent structure. From the Cuppy well, we can determine that the average seismic velocity of the strata overlying the granite is locally approximately 4785 m/s (15,700 ft/s). This velocity value was used to estimate depths to and thickness above the granite basement.



**Figure 5.** Location of the seismic line used to illustrate Precambrian basement highs on seismic reflection data. The Texaco Cuppy well drilled through the Eau Claire directly into granite and never encountered Mt. Simon. The outlined areas are producing oil fields. The oil fields with a diagonal line pattern had seismic reflection data confirm a Precambrian basement high. The other oil fields on this map had no available seismic data.

The upper correlated seismic horizon on this seismic profile (Figure 6) represents the base of the Knox Dolomite, a thick carbonate succession that commonly does not have any strong internal seismic reflections. The high amplitude reflectors directly under the Knox are generated from the Eau Claire Formation; however, some of this reflectivity is likely to be short-path multiples (reverberation). Poststack deconvolution tests were performed to remove this effect and indicate some reduction in reflection cyclicity while retaining

the basic character shown in Figure 6. The lower correlated seismic horizon represents the top of the Precambrian basement. A distinct difference in the seismic character is observed, especially based on the instantaneous phase attribute, between the sedimentary strata above and the granitic rocks below the Precambrian basement seismic horizon. The lack of continuity can be seen when the seismic-phase attribute is displayed instead of amplitude (Figure 6b). The seismic-phase attribute enhances variations in bed continuity. The contrast



**Figure 6.** North–south seismic profile illustrating Precambrian basement paleotopography. The sediment fill in the low area is either Eau Claire or Mt. Simon. The three displays are all of the same profile but (a) is a display of the seismic amplitude, (b) is a display of the phase attribute, and (c) is the seismic data with the base of the Knox horizon being flattened. The Texaco Cuppy well encountered some Eau Claire, but no Mt. Simon was found and instead the well was drilled into granite.

between spatial continuity and discontinuity is emphasized by the phase attribute so that stratal pinch-outs, angular unconformities, and fault offsets are highlighted. Because amplitude information is not processed, strong and weak events tend to be represented equally. The reader is referred to Taner and Sheriff (1977), Bodine (1986), and Taner (2001) for more explanation on the use of seismic attributes for interpreting seismic reflection data.

The best seismic marker in the deeper section of the Illinois Basin is the base of the Knox. This marker is close to the base of the Knox Supergroup but may not be exactly at the actual boundary as correlated on wireline logs. Unconformities between the Knox and the underlying Eau Claire are unknown in the study area; therefore, one can safely assume that these horizons were deposited as horizontal beds, and flattening on the base of the Knox would give a good representation

of the topography of the Precambrian basement. The flattened profile (Figure 6c) shows that the basement topography had a maximum relief of more than 610 m (2000 ft) over a distance of 4.8 km (3 mi), with most of the change in topography happening over less than 1.6 km (1 mi). In this area, the Eau Claire is significantly thicker, and much of the sedimentary fill in the topographic low areas is not Mt. Simon but instead is a different facies of the Eau Claire.

In the study area of Hamilton and White counties, the seismic reflection data suggest that because of structural drape, a strong relationship exists between oil production in the shallower Mississippian-age strata and basement highs. The oil fields with the diagonal pattern (Figure 5) all had seismic reflection data that showed them to be underlain by basement highs. We hypothesize that the underlying basement topography can be loosely visualized by looking at the shape and placement

of the overlying oil fields. The relationship between basement highs and oil production has only been observed in this local area and has not been observed in areas with extensive seismic control north of the study area. The relationship of basement highs to production is important not because of its predictive capabilities across the basin, but because it may illustrate the Precambrian topography of Illinois. There may be some tectonic overprint on the oil field shape. For example, the northeast orientation of the oil fields in the eastern part of the map has the same strike as the northeast strike of the Wabash Valley fault system. From the oil field map, we can estimate that the Precambrian basement highs are less than 8 km (5 mi) in width and no more than 24 km (15 mi) in length with most being less than 1.6 km (1 mi) in diameter. The length of the basement high features is probably less than our estimate based on the oil field size because of the tectonic overprint from the Wabash Valley fault system.

#### **RELATIONSHIP OF PRECAMBRIAN TOPOGRAPHY AND RESERVOIR THICKNESS AND QUALITY**

The identification of the Precambrian basement highs that predate Cambrian sedimentation is important because the Mt. Simon is thin or absent at these highs. However, a thick succession of Mt. Simon can be expected off the flanks of these basement highs. The Mt. Simon commonly has an arkose-rich interval that is 6 to 12 m (20 to 40 ft) thick but can range up to 122 m (400 ft) that occurs near the base of the Mt. Simon. This is similar to what is observed at the Mt. Simon outcrops in Missouri (Houseknecht and Ethridge, 1978). In places, more than 549 m (1800 ft) of topographic relief on the basement surface is observed.

In the St. Francois Mountains of Missouri, the Lamotte (equivalent to Mt. Simon in Illinois) was deposited as part of an alluvial fan and braided fluvial system surrounding basement paleohighs (Houseknecht and Ethridge, 1978). The Mt. Simon lithology of this system is described as arkosic conglomerates.

In the subsurface of Illinois (Figure 3), we found numerous arkose-rich intervals near the base of the Mt. Simon. The arkosic interval, because of its high feldspar content, is more prone to secondary porosity development than the more quartz-rich parts of the Mt. Simon. The interval labeled arkose on the wireline log of the Hinton 7 (Figure 3) had sidewall core mea-

surements exceeding 25% porosity and permeabilities of more than 1 d (Leetaru et al., in press) at a measured depth of 1800 m (5900 ft). In other wells in the basin, the basal Mt. Simon Sandstone had measured porosities of close to 30% at depths of 2468 m (8100 ft).

Workman and Bell (1948) described a Precambrian high in west-central Illinois (Pike County) where the first well drilled encountered no Mt. Simon. A second well drilled 12.8 km (8 mi) to the north of the Precambrian high encountered 136 m (445 ft) of sandstone grading downward to a basal pebble conglomerate (20 m [65 ft] thick). The resistivity curve on the wireline log suggests that the basal conglomerate had significantly better porosity than the overlying Mt. Simon sandstone. Later additional wells in this area also show increases in reservoir porosity in the basal Mt. Simon.

Both outcrops and subsurface data suggest enhanced reservoir quality around the flanks of the Precambrian basement highs. Therefore, although the Mt. Simon is thinner along the western and southern areas of Illinois, a good target reservoir for carbon sequestration in areas surrounding basement features still exists.

Note that some of these alluvial fan deposits could be widespread braided river deposits in the thicker parts of the Mt. Simon that are not localized around basement highs. These braided river deposits are also arkosic, have good reservoir properties, and have been found in both the subsurface and outcrops.

#### **CONCLUSIONS**

The mapping of basement paleotopography with seismic reflection profiles is mandatory in areas known to have thin (e.g., less than 244 m [800 ft]) Mt. Simon strata and would be strongly recommended in all areas of the basin. Precambrian basement highs should be avoided if they have relief sufficient to eliminate the potential for Mt. Simon deposition. At the least, they are higher risks for developing sequestration projects.

The Mt. Simon along the flanks of paleohighs is a potential sequestration target. There should be significant increases in reservoir quality in the basal Mt. Simon because of the potential for deposition of alluvial fans and/or braided river deposits. The only caveat is that if the basement feature was too high, then there may be no sealing facies on the high relief area because the Eau Claire Formation may never have been deposited.

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