Fine-scale structure of the Precambrian beneath the Illinois Basin

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ABSTRACT

Increasing our understanding of the heterogeneity of Precambrian crust continues to be a focus for deep seismic reflection studies. High-resolution two-dimensional (2D) seismic profiles and a high-resolution 3D seismic volume, all centered on Decatur (Illinois, USA), provide new insights on the structure and composition of Precambrian basement beneath the Illinois Basin of the central USA midcontinent. The new data reveal a pattern of strong and coherent reflections and associated diffractions deeply buried within the eastern Granite-Rhyolite Province. This pattern is dominated by a thick seismic stratigraphic sequence, which is wedge or bowl shaped in cross section and has an angular unconformity with the overlying Paleozoic section. Deeper intrabasement bowl-shaped sequences or series are also observed in the same area. We interpret these features to be a northward continuation of analogous basement sequences located 75 km to the south below the southern part of the Illinois Basin. This correlation indicates a vast Precambrian province with a north-south dimension of >200 km. Although multiple explanations are admissible for the Precambrian reflectivity, the most likely for our study area is igneous intrusion of broad mafic igneous (diabase?) sills possibly underlain by small plutons. The concentration of such mafic (or bimodal) igneous activity within or coeval with the eastern Granite-Rhyolite Province suggests an episode of Proterozoic crustal extension and rifting.

INTRODUCTION

The expansion of major national geophysical investigations into the United States midcontinent has increased the focus on intracratonic deep-Earth structure in areas like the Illinois Basin (e.g., EarthScope, 2015, www.earthscope.org). However, the application of petroleum industry strategies such as high-resolution two-dimensional (2D) and 3D seismic reflection data has lagged. While classic seismic refraction, seismic tomography, and potential field studies have increased our understanding of broad-scale structure of the Earth’s crust and upper mantle beneath the Illinois Basin and the surrounding region (e.g., Pratt et al., 1992; Bedle and van der Lee, 2006; Liang and Langston, 2008; Yang et al., 2009; Chu et al., 2012; Hamburger et al., 2011b; Foster et al., 2014; Gallegos et al., 2014), detailed data for the deeply buried Precambrian are usually not available. A persistent challenge for crustal geophysical studies in general is how to explain strong subhorizontal seismic reflections (sometimes termed bright spots) in the deep continental crust. Our study provides one of the best geophysically constrained observations of such reflectivity in a classic area of geological interest. Recent advancements in 2D and 3D seismic imaging, applied as part of a carbon sequestration program in the Illinois Basin (Couéslan et al., 2009, 2013, 2014a, 2014b; Leetaru et al., 2009; Alvi et al., 2013; McBride et al., 2014), provide a unique opportunity to employ state-of-the-art techniques to studying Precambrian geology beneath the basin.

Outstanding questions that can be addressed by high-resolution 2D and 3D seismic data are: (1) what is the degree of heterogeneity in Precambrian crust, including that related to isolated strong reflectors interpretable as tabular igneous intrusions (e.g., mafic igneous sills); (2) is there evidence of bimodal volcanism beneath the Paleozoic Illinois Basin; (3) what is the extent of stratigraphic sequences in what has traditionally been called basement beneath the Illinois Basin; and (4) is there anything new to be learned about the Precambrian from fine-scale 2D and 3D seismic imaging?

GEOLOGICAL BACKGROUND

The Illinois Basin (Fig. 1A) is filled with as much as 7 km of Paleozoic sedimentary rocks ranging from early or middle Cambrian to early Permian (Collinson et al., 1988). Although the Illinois Basin has been characterized as a classic sag basin (Buschbach and Kolata, 1991), the geology of the deep subsurface has a complex history of faulting, Precambrian basement uplifts, and folding (Nelson, 1995; McBride and Nelson, 1999; Leetaru and McBride, 2009). Contractional deformation, as observed from borehole and sparse geophysical data, occurred over a broad span of Paleozoic time, culminating in Late Pennsylvanian and early Permian and corresponding to the Alleghanian orogeny in the Appalachians (Kolata and Nelson, 1991).

Geophysical interpretation of the lower Paleozoic and deeper crustal structure beneath the basin has been constrained by regional seismic profiles (Bartagne and Leising, 1991; Heigold and Otzt, 1991; Pratt et al., 1992; Bear et al., 1997; Potter et al., 1995, 1997; McBride and Kolata, 1999; McBride et al., 2003), potential field data (Pratt et al., 1992; Heigold and Kolata, 1993; Hildenbrand et al., 2002; McBride et al., 2002; Okure and McBride, 2006), regional seismic refraction profiles (Heigold, 1991; Catchings, 1999; Chulick and Mooney, 2002), and by analysis of earthquakes (e.g., Kim, 2003; Hamburger et al., 2011a).

The Cambrian Mount Simon Sandstone has for many years been the primary target in the basin for gas storage and for carbon dioxide sequestration (Morse and Leetaru, 2005; Leetaru et al., 2009; Leetaru and McBride, 2009). Accordingly, much is known about this unit, especially compared to the under-
lying Precambrian basement (Coueslán et al., 2009, 2014a, 2014b; Leetaru et al., 2009). The Precambrian beneath the basin comprises heterogeneous granitic composition igneous rocks and/or related metasedimentary strata, all presumably belonging to the eastern Granite-Rhyolite Province (EGRP; Sargent, 1991; Pratt et al., 1992; Van Schmus et al., 1996; McBride et al., 2003, 2010; Fig. 1A). The EGRP extends as a band of diachronous basement rocks from northern Mexico to Quebec (Karlrstrom et al., 1999). These rocks, where exposed in the St. Francois Mountains (Ozark dome of southeastern Missouri), are 1480–1460 Ma (Bickford et al., 1986; Van Schmus et al., 1996; Rohs and Van Schmus, 2007; Thomas et al., 2012); this means that the unconformity at the base of the Paleozoic section represents almost 1 b.y. of missing geologic time.

Regional and local drill-hole data for our study area (Figs. 1B, 1C) indicate that these same rocks extend beneath the Illinois Basin (McBride et al., 2010).

The origin of the EGRP is not well understood. Because the province includes A-type granites, the rocks are thought to have been emplaced in an extensional plate tectonic setting, as opposed to along an active convergent margin (Dall’Agnol et al., 2005). Lidiak (1996) argued for an intraplate extensional tectonic setting based on geochemical data. Van Schmus et al. (1987) interpreted the EGRP to have been derived from partial melting of older Proterozoic lower continental crust. Van Schmus et al. (1996) used geochemical modeling based on rare earth elements (samarium and neodymium) to postulate a major geological boundary cutting diagonally across the central midcontinent, including the EGRP (Fig. 1A). This boundary, which is interpreted to separate Paleoproterozoic lower crust to the northwest from Mesoproterozoic lower crust to the southeast, is thought to have once marked the edge of the older part of the Laurentian continental margin (Van Schmus et al., 1996; see also Hoffman, 1989; Karlstrom et al., 1999).

PREVIOUS STUDIES

The new 2D and 3D seismic data are situated over the northwestern flank of the Illinois Basin, where the depth to the Precambrian basement is locally 2183 m below sea level, as measured from the CCS1 well (Fig. 2), and regionally –1000–2500 m below sea level as known from deep drill holes within the basin (Fig. 1B). Acquisition and processing of the 2D seismic profiles were performed during a U.S. Department of Energy study on the Cambrian–Ordovician strata of Illinois and Michigan (Leetaru, 2014). For reference, the site of the 3D seismic survey, where the three 2D profiles intersect (Fig. 1C), is located 75 km north of the nearest comparable regional seismic profiles (McBride et al., 2003, 2010). Previous geological interpretation of 3D seismic data in the Illinois Basin has been based on small surveys, including from the Tonti and Stewardson Dome east oil fields (McBride et al., 2008, 2014) in central Illinois, and from the U.S. Department of Energy National Energy Technology Laboratory Illinois Basin–Decatur Project (IBDP) in Decatur, Illinois (Coueslán et al., 2014a, 2014b). These studies focused primarily on the lowermost Paleozoic section and top of Precambrian basement. Our study is focused solely on the Precambrian.

METHODS

The IBDP study area is centered on Decatur, Illinois, which has been the site of intensive testing of carbon dioxide injection and monitoring using dedicated drill holes (Figs. 1C and 2) and 2D and 3D seismic reflection data (Coueslán et al., 2014a, 2014b). This means that the Decatur site has one of the best sets of geophysical and geological constraints in the Illinois Basin for studying Precambrian basement. It is ideal for integrating fine-scale interpretations of deep
Precambrian rocks from 2D and 3D seismic data, the former providing a broad regional context and the latter revealing high-resolution information, unprecedented for the Precambrian beneath the basin.

The new regional profiles were acquired in 3 separate lines totaling almost 200 km (Fig. 1B; Leetaru, 2014). In order to optimize the utility of the 2D seismic data, all three profiles intersected one another within or close to the 3D seismic volume (Figs. 1B, 1C). The seismic source for the 2D profiles consisted of a Hemi-44 20,412 kg vibrator (4 sweeps, 4–100 Hz, and a sweep length of 18 s), with a source interval of 36.6 m, a receiver interval of 3 m, a listening time of 5 s, and processed into a common midpoint (CMP) interval of 6.1 m. The close spacing of receiver and source elements (especially the latter) furnish a high-resolution image, unlike anything previously available in the Illinois Basin. CMP data processing included prestack and poststack noise reduction, refraction and residual statics corrections, surface-consistent deconvolution, automatic gain control, velocity analysis for normal move-out corrections, radon multiple attenuation, and stacking with a nominal fold of 60. The southern and western portions of lines 601 and 501, respectively, suffered from the effects of decreasing CMP fold and noise from industrial and cultural installations as they entered northeastern Decatur (Fig. 1C). Although both migrated and unmigrated data were examined for this study, the 2D profiles are shown unmigrated in order to preserve information on diffraction structure. Because detailed seismic velocity information needed to convert the seismic data from traveltime to depth are only available for the 3D volume (Couëslan et al., 2013), all seismic data are shown as traveltime sections.

The 3D data volume at the IBDP site had 10.17 km² of surface coverage. The seismic source was 2 AHV-IV Buggy vibrators (fundamental ground force was 19,845 kg) per station with 2 sweeps per vibrator, a sweep length of 12 s, and a listening time of 5 s (sweeping 2–100 Hz). The source line and point intervals were 219.5 m and 24.4 m, respectively. The receiver line and single-sensor intervals were 195.1 m and 3.0 m, respectively. Nominal CMP fold is 68 with a bin size of 12.2 m × 12.2 m and bin density of 53,858/km². All parameters combine to provide a high degree of spatial resolution.
RESULTS

Primary Observations

The primary result of the seismic data is that the typically highly reflective, well-layered, and relatively flat-lying Paleozoic section overlies a more complex and structured Precambrian basement (basement surface is approximately the base of Cambrian Mount Simon Sandstone) (Fig. 2), as observed further south in the Illinois Basin (Heigold and Oltz, 1991; Pratt et al., 1992; McBride et al., 2003). Locally, the Paleozoic-Precambrian basement contact is defined from the three deep wells (Fig. 1C) (Couëslen et al., 2014a, 2014b) drilled into the 3D seismic volume (the lower part of the CCS1 well log is shown in Fig. 2). Well logs show the contact as clastic sediments overlying a rhyolite and/or its eroded products (Fig. 2). U-Pb isotope dating of zircons indicates the age of the rhyolite formation to be 1467 ± 25 Ma (Leetaru and Freiburg, 2014). As discussed in detail by Couëslen et al. (2013), results from a vertical seismic profile (VSP) were used to correlate the top of Precambrian basement with the 3D reflection data, which can then be correlated into the intersecting 2D profiles (Fig. 1C). Unlike many of the Paleozoic seismic stratigraphic markers (e.g., the base of the Cambrian-Ordovician Knox Group), the top of basement...
in this area is not always a strong reflector. Our study focuses on the reflectivity structure beneath the top of basement (~1000–4000 ms for 2D data and 1000–2000 ms for 3D volume).

2D Seismic Profile Observations

The regional 2D profiles (Figs. 3A–3C) below ~1.1 s are dominated by two broad, concave-upward or bowl-shaped reflectors or thin series of reflectors, each of which become shallow to the west and to the east. This pattern is best seen on the east-west line 101 and an intersecting north-south line 601 (see IpC markers in Figs. 3A and 3B, respectively). The rocks corresponding to the traveltime interval between the base of the Mount Simon Sandstone and the basement reflector are referred to as a sequence, even though it is not necessarily internally reflective. Based on a P-wave velocity of 6 km/s, typical for granitic igneous basement rocks (McBride et al., 2003), the maximum thickness of the sequence along line 101 (Fig. 3A) is ~2280 m. Along the western edge of the sequence, the apparent dip of the basal reflector (IpC) is ~10° to the east. The shape of the basal reflector is complex, with abrupt terminations (e.g., below station 214300, line 101; Fig. 3A) and lateral changes in the number of cycles (e.g., below station 22500, line 101; Fig. 3A). The shallowest part of the basal reflector is truncated by the relatively horizontal or gently structured top of the basement (see western part of Fig. 3A). The westernmost part of line 501 (Fig. 3C), due to its oblique orientation with respect to the geometry of the sequence, only shows a weak expression of the basal reflector. Nevertheless, line 501 pinpoints the location of the pinchout of the sequence on the east (see IpC markers in Fig. 3C), confirming the overall bowl shape. Line 601, despite a severe noise problem near its south end where the CDP fold is low and interference from ground infrastructure is high, extends the observations from lines 101 and 501 by revealing a prominent component of southward thinning of the sequence.

The interior of the intrabasement sequence on the 2D profiles is poorly reflective, especially with respect to the overlying Paleozoic section. Some horizontal events beneath the base of the Mount Simon Sandstone could be interpreted as primary reflections (horizontal arrows, Fig. 3A); however, they may only be multiple reflections generated in the strongly reflective and well-layered Paleozoic section.

Below the base of the intrabasement sequence (IpC) are long and short segments of reflectivity, including diffractive zones, which are less coherent than the base of the sequence. These reflections (DpC in Figs. 3A–3C) are subhorizontal or east dipping (in the plane of the section), mimicking, but not parallel to, the base of the overlying sequence. A series of deep reflections on line 501 can be interpreted to describe a deeper bowl-shaped sequence,
analogous to, but much deeper than, the sequence on line 101. Note that this series of reflectors does not form an angular unconformity with the base of the Paleozoic section. The 3D orientation of these reflectors and/or diffractors is unknown; they are not covered by the 3D seismic data volume (discussed in the following).

### 3D Seismic Volume Observations

The three 2D regional profiles are tied together within or near the 3D seismic volume (Fig. 1C), thereby allowing an accurate image of Precambrian reflectivity that can be extended well beyond the volume. Optimally oriented vertical extracts from the 3D volume reveal the same prominent basement dipping reflector, which lies with the dipping basal reflector imaged on the three 2D profiles (note that the deeper basement series on line 501 is not covered by the volume). On the volume, coherency and location accuracy are improved by 3D seismic migration. North-south profiles from the volume (Fig. 4) indicate a strong north-dipping component to the basal reflector. An east-west profile (Fig. 5) provides a purely strike view of the same reflector. A dip profile (with respect to the dip of the basal reflector) (Fig. 6) shows the basal reflector with a true dip of 16° to the northwest (using the VSP for depth conversion; Couëslan et al., 2013). This profile also reveals the structural behavior of the reflector as it flattens abruptly to the north, before plunging deeper where it intersects 2D line 101 (Fig. 3A).

Horizon mapping from the 3D volume furnished detailed information on the structure of the top- and infra-Precambrian surfaces (Figs. 7A and 7B, respectively). The top of basement reflector, as mapped only from the 3D volume, defines two prominent oblong or circular domes (in plan view) (Fig. 7A) separated by a narrow east-west-oriented trough (see also Couëslan et al., 2014a). The surface for the dipping basement reflector indicates fine-scale complexity, including small offsets and disruptions (Fig. 7B). As observed on the 3D vol-

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**Figure 3 (on this and following page).** (A) Excerpt from two-dimensional seismic line (unmigrated) 101 (see Fig. 1B for location). NA—base of Devonian New Albany Shale; Kx—base of Ordovician Knox Supergroup; pC—top of Precambrian basement (approximately the base of the Mount Simon Sandstone); IpC—intra-Precambrian reflector (base of shallow Precambrian sequence discussed in text); DpC—deep Precambrian reflector. Horizontal arrows show possible primary stratal reflectors cut off by the IpC reflector. The black brackets identify the shallow bowl-shaped reflection series discussed in the text (see Fig. 1B). V.E.—vertical exaggeration.
On vertical views generated from the volume, the bowl-shaped sequence is expressed as wedge shaped owing to the location of the volume along the southern margin of the larger structure (cf. Figs. 6 and 8). A noticeable difference between 2D and 3D vertical views is a fabric of apparent horizontal reflectivity on the latter that is absent or much less observed on 2D views (e.g., 1.1–1.5 s; Fig. 6). At first glance, the horizontal reflections appear to represent intrabasement layering, suggesting a possible stratigraphic origin. In particular, the basal reflector (IpC) that defines the eastern and

Figure 3 (continued). (B) As in A, but showing all of line 601. (C) As in A, but showing all of line 501. The green brackets identify the deep bowl-shaped reflection series discussed in the text (see Fig. 1B). The two depths indicated by the two horizontal arrows are derived from the CCS1 drill hole (Fig. 2) and assuming a bulk upper Precambrian crust seismic velocity of 6 km/s (this applies to all subsequent vertical views). Note that all profiles are shown unmigrated in order to preserve the effects of diffraction.
western margins of bowl-shaped Precambrian sequence on line 101 appears to truncate a series of reflection events within the sequence (two horizontal arrows in Fig. 3A). However, in order to examine the idea that the horizontal reflectivity could be a complex series of multiple reflections, we used the 3D volume to carefully map one event within this series (Fig. 9) between the dipping reflector and the base of the Mount Simon Sandstone (top of basement). We then compared the traveltime structure of this reflection to the top of basement reflector. The result shows a strong match of positive and negative traveltime features (Fig. 9). This suggests that the mapped intrabasement horizon is actually part of a multiple reflection series generated in the well-layered Paleozoic section above. Autocorrelation tests (Yilmaz, 2001) computed on the stacked data show evidence of residual multiple contamination that could be propagating into the section after ~1.1 s, which could account for the spurious horizontal reflectivity there (Fig. 10).
The new 2D and 3D seismic reflection data provide the most detailed view available of Precambrian reflectivity beneath the Illinois Basin, and for the EGRP in general. The reflectivity in deep basement rocks is as relatively strong as, or even stronger and more coherent than, the well-layered reflectivity typical of the overlying Paleozoic sedimentary section (Fig. 3A). The deep reflectivity is distinguished from the Paleozoic section by indicating dipping and structurally complex surfaces. The basement reflectivity documented in this study, centered around Decatur, Illinois, is likely part of (or closely related to) another broad, regional pattern of reflective basement sequences, expressed as a large basinal depression at least 225 km wide (east-west) and 120 km long.
The western tapered edge of the shallower bowl-shaped sequence on line 101 matches the northward extrapolation of the western edge of the basement sequences to the south (Fig. 11). A correlation between the two areas suggests a vast Precambrian province underlying the Illinois Basin with a north-south dimension of >200 km.

There are, however, significant differences between the Precambrian reflectivity of the two areas (Fig. 11): the sub-Mount Simon Sandstone to the north shows little or no reflectivity other than the strong isolated reflectors, whereas to the south, the sub-Mount Simon is strongly layered and shows apparent stratigraphic features in addition to strong isolated reflectors (McBride and Kolata, 1999). Furthermore, the northern area is dominated by a broad, ...
Figure 7 (on this and following page).  
(A) Traveltime structure map, based only on the three-dimensional seismic volume, for the base of the Cambrian Mount Simon Sandstone (approximately the top of Precambrian granitic basement). See Figure 1C for location. NAD—North American Datum.
Figure 7 (continued). (B) As in A, but for dipping intrabasement reflector (Ipc reflector). Arrows indicate northwest-trending ridge discussed in the text.
closed-contour and high-amplitude magnetic anomaly (Fig. 12), while only a portion of the southern area shows anomalies, which are less well defined. We suggest that the Precambrian of the northern area may have a relatively high concentration of magnetic igneous plutons or sills that can account for the major anomaly there.

Three explanations can be proposed for the origin of the strong Precambrian reflectivity within the EGRP beneath the Illinois Basin: (1) part of a thick undocumented sedimentary basin beneath the Illinois Basin Paleozoic; (2) part of a layered sequence of felsic volcaniclastic deposits; (3) mafic igneous sills intruded into a granitic country rock.

Thick Precambrian sedimentary strata have been proposed to lie beneath a portion of the Illinois Basin of east-central Illinois and eastward into Indiana, Ohio, Kentucky, and adjoining areas (Shrake et al., 1990, 1991; Drahovzal et al., 1992; Drahovzal, 1997). These deposits, which include the Middle Run Formation (Shrake et al., 1990), are estimated to be 1.2–1.0 Ga (Keweenawan age) based on limited drill-hole control and seismic reflection profiles located east of Illinois (Drahovzal et al., 1992; Baranoski et al., 2009). Layers of basalt have been observed in drill holes in Kentucky within and overlying the Middle Run Formation (Drahovzal et al., 1992). A Keweenawan age for the Middle Run Formation would indicate that the sediments are considerably younger than the EGRP rocks found in drill holes beneath the study area. Furthermore, sedimentary strata correlative to the Middle Run Formation have not been observed from deep drill holes in the study area or vicinity (McBride et al., 2010). Available information from drill holes into the Precambrian basement of Illinois indicates granitic-rhyolitic compositions and textures (Sargent, 1993; McBride et al., 2010).

From observations on regional seismic profiles in the southern Illinois Basin, McBride et al. (2003) described a stacked series of seismic stratigraphic sequences of interpreted volcaniclastic origin for the uppermost Precambrian. These sequences, which include the Centralia sequence (Pratt et al., 1992), are mapped over a large area of southern Illinois and western Indiana (Fig. 11), where regional seismic reflection data are available. However, we do not observe a well-developed layering on the new seismic profiles and 3D data. Most layering appears to be only apparent, most prominently on the 3D volume (Fig. 9). Instead, the reflection pattern is defined by two broad, bowl-shaped basal surfaces, the shallowest of which continues up to and is truncated by...
Figure 9. Comparison of base of the Cambrian Mount Simon Sandstone reflection (approximately the top of Precambrian basement) traveltime structure and apparent subhorizontal intra-Precambrian reflection arriving before the dipping basement reflection (see Fig. 7B). NAD—North American Datum. Vertical arrows show correspondence of traveltime highs and lows between the two reflections, which suggests that the subhorizontal reflection is actually a multiple arrival. See text for more discussion.
the base of the Mount Simon Sandstone, without obvious internal reflectivity. Likewise, the deeper bowl-shaped series imaged only on line 501 (Fig. 3C) appears to be an isolated feature with no layered reflectivity above or below it.

We conclude that the most acceptable interpretation for the Precambrian reflectivity beneath our study area is mafic igneous (e.g., diabase) sills intruded into a granitic-rhyolitic country rock. Strong intrabasement Precambrian reflectors and sequences of reflectors have been imaged previously on long-record seismic profiles from a variety of settings outside the Illinois Basin (e.g., Juhlin, 1990; Litak et al., 1991; Pratt et al., 1992; BABEL Working Group, 1993; Papasikas and Juhlin, 1997). Most studies of mafic igneous sills, as expressed on seismic reflection data, describe intrusion into the deep strata of a sedimentary basin (Planke et al., 2005; Thomson and Hutton, 2004; Magee et al., 2015), but diabase sills are also interpreted from a granitic basement host rock in other geologic settings (Juhlin, 1990; Litak et al., 1991). Detailed interpretations of diabase (or other mafic igneous) sills and intrusive complexes were made from 2D and 3D seismic data from the North Sea and the Rockall Trough by Polteau et al.
McBride et al. (2003, 2010) and for this study (3D—three dimensional). Enlarge-ment shows detail of contours of shallow Precambrian sequence discussed herein. Contours are in seconds, two-way travel-time. Blue dashed line represents geo-chemically defined crustal boundary postu-lated by Van Schmus et al. (1996) (Fig. 1A).

Figure 11. Regional traveltime structural contour map for base of Precambrian reflection sequences in southern Illinois (McBride et al., 2003, 2010) and for this study (3D—three dimensional). Enlarge-ment shows detail of contours of shallow Precambrian sequence discussed herein. Contours are in seconds, two-way travel-time. Blue dashed line represents geo-chemically defined crustal boundary postu-lated by Van Schmus et al. (1996) (Fig. 1A).

Diabase intrusions are typically interpreted on seismic profiles on the basis of high amplitude (from the impedance contrast between high P-wave velocity diabase and granitic or sedimentary country rock), strong lateral continuity, nonconcordant relationships with the country rock (e.g., crosscutting relationships with other reflectors, if present), cutting upsection within Precambrian basement or in a deep part of a sedimentary section, abrupt terminations, and perhaps most important, an overall bowl shape in profile (Litak et al., 1991; Malthe-Sørenssen et al., 2004; Planke et al., 2005; Polteau et al., 2008; Magee (2008), Thomson and Hutton (2014), Magee et al. (2015), and others. In one of the best-documented cases, high-amplitude subhorizontal reflections from the Siljan Ring impact structure in central Sweden have been shown to correlate with diabase sills intruded into Precambrian granite at depths of 4500 m and greater, based on a deep drill hole (Juhlin, 1990; Papasikas and Juhlin, 1997). These deep reflections are similar to those observed on the Illinois profiles, in terms of high-amplitude, coherency, and showing an overall concave-upward (bowl) shaped structure.
DISCUSSION

An almost ubiquitous feature of deep seismic reflection profiles of continental crust is relatively isolated horizontal or gently dipping high-amplitude reflectors. In many cases, these reflectors are so strong and coherent as to be considered bright spots. The occurrence of high-amplitude reflections in deep Precambrian crust, traditionally considered to be more or less homogeneous, suggests significant lithologic heterogeneity. Such features are described from many disparate geological environments worldwide. Explanations span a broad range: an active shear zone or the brittle-ductile transition in the crust (Ryberg and Fuis, 1998; Liotta and Ranalli, 1999; Brogi et al., 2005), detachment faults (Allmendinger et al., 1983; Reston, 1996), aqueous fluids or molten material (de Voogd et al., 1986; Makovsky et al., 1996; Makovsky and Klemperer, 1999), or mafic igneous sills (Goodwin et al., 1989). Any of these features have sufficient acoustic impedance contrasts to produce high-amplitude reflections or sequences of reflections. Without good 3D volumetric constraints, such reflections cannot be interpreted uniquely. For example, the Surrency bright spot, a prominent isolated deep crustal reflection observed in the core of the late Paleozoic suture between Laurentian and African proto-Atlantic terranes, was originally interpreted as evidence of fluids in crystalline igneous crust (Pratt et al., 1991). This feature was, however, later interpreted as more likely a diabase sill related to the Mesozoic crustal extension that followed continental suturing (Pratt et al., 1991; Barnes and Reston, 1992). The interpretation of the Death Valley bright spot as partially molten material in deep continental crust was supported by an apparent spatial association with Cenozoic volcanoes at the Earth’s surface (de Voogd et al., 1986). Both of these cases were, like almost all deep seismic reflection studies, limited by access to only one long, regional profile. It is rare to have imaging of such isolated bright reflectors on multiple intersecting 2D seismic profiles that are validated by a 3D seismic volume, as in our study.

A significant concentration of mafic igneous rocks buried within the upper and/or middle crust should produce a significant potential field anomaly. Comparing results from the seismic data with a reduced-to-pole first vertical derivative magnetic intensity map (Figs. 1C and 12) shows a correspondence of the shallow bowl-shaped sequence on line 101 with a prominent, isolated anomaly. The Precambrian reflectivity centered on the strong anomaly is not found elsewhere on the 180-km-long transect. An isostatic gravity anomaly map (Daniels et al., 2008) also shows an anomaly, albeit less prominent relative to nearby gravity anomalies. This correspondence is consistent with a zone of intrusion of mafic igneous rock with expected higher magnetization, as described elsewhere for magnetic anomalies within the Illinois Basin (McBride et al., 2003). Given this context, the enigmatic zones of prominent, high-amplitude reflections and diffractions (DcP in Figs. 3A–3C) below the bowl-shaped sequence on line 101 may be expressions of deeper isolated mafic igneous sills and small plutons. Note that the deeper bowl-shaped reflection series on line 501 located to the east does not correspond to a significant magnetic anomaly; this suggests that the deep crust directly beneath the large closed-contour
anomaly was intruded by a pluton that could have been the source for sills or tabular intrusions in the shallower crust to the east.

Forward modeling of the observed magnetic intensity pattern was considered, but deemed impractical due to the limited spatial coverage of the seismic data, relative to the much larger anomaly (and anomalies); furthermore, although the seismic images provide constraints on the uppermost parts of the interpreted sills or plutons, they cannot constrain the lower limits of these bodies. Planke et al. (2014, p. 15) noted that “if sills are buried below more than a few kilometers of sediments,” magnetic anomaly modeling may have poor resolution. Nevertheless, we can call upon analogous relationships between better studied (or exposed) mafic igneous intrusions and magnetic anomalies in order to provide guidance for interpreting the associations we observe. Perhaps the most relevant example is that from the St. Francois Mountains in southeast Missouri (located a little more than 250 km southwest of our study area), where strong positive magnetic anomalies have been conclusively correlated to mafic igneous rocks (including diabase) intruded within a granitic host rock (Kisvarsanyi, 1974; Hildenbrand et al., 1982, 1996). As described here, this granitic host rock is part of the EGRP, which extends beneath our study area in central Illinois (Fig. 1A).

Cases of magnetic anomaly modeling of mafic igneous sills can be found for very well constrained geologic settings. For example, Krassay et al. (2013) demonstrated the utility of forward magnetic anomaly modeling of interpreted mafic igneous sills or tabular intrusions within sedimentary basins when high-resolution magnetic intensity data and a coincident grid or network of seismic profiles are available. In the southern Illinois Basin, occasional positive magnetic anomalies have been shown to be related to shallow ultramafic igneous sills intruded into Paleozoic sediments by forward modeling of high-resolution magnetic intensity data (Sparlin and Lewis, 1994). In both of these cases, the sills or series of sills, which individually ranged in thickness from 72 m to a few hundred meters, produced magnetic anomalies of 100–250 nT.

A direct interpretation of the exact geometry of hypothetical igneous bodies is not possible, because the seismic method cannot easily record reflections from a steep or vertical interface. Furthermore, imaging the base and internal structure of an igneous body is generally not possible due to attenuation of signal within the body and the lack of strong impedance contrasts within it, including its base (Luke, 2012). Given these caveats, we envision a group of signal within the body and the lack of strong impedance contrasts within the body and the lack of strong impedance contrasts within it, including its base (Luke, 2012). Given these caveats, we envision a group of mafic igneous plutons and sills that are genetically related and concentrated beneath the bowl-shaped sequence best expressed on line 101 (Fig. 13). The dimensions of the bowl-shaped sequence in our study area are larger than those of most mafic igneous sill sequences described from sedimentary basins (see discussion here); however, our feature, which is almost 30 km wide in an east-west cross section (Fig. 8C), is comparable to the dimensions of the Golden Valley diabase sill of the Karoo Basin of South Africa (Galerne et al., 2011). The Golden Valley diabase sill has a long dimension of ~20 km (Chevallier and Woodford, 1999). The Great Whin and Midland Valley diabase sill complexes of northern England and southern Scotland crop out over several tens of kilometers (Goulty, 2005).

Due to our limited data coverage, the full 3D distribution of the interpreted sills is unknown; however, in order to derive dimensions, for comparison purposes, we have calculated a rough hypothetical areal extent, based on the projection up to the ground surface assuming the maximum north-south width and east-west extent of the gridded horizon (Fig. 8) to be 9.3 km × 27.5 km = 255.8 km². The actual area is likely to be much larger, so this is a conservative estimate. Next we used the high-resolution 3D volume to measure a traveltime interval for the basal reflector to be typically ~50 ms and assumed this value to represent the interpreted sill thickness. Assuming a typical upper crustal P-wave seismic velocity (6 km/s), this traveltime converts to 150 m. This is not greatly different from the thickness of the Siljan Ring diabase sills (as much as 60 m thick), as confirmed by drilling and imaged as strong subhorizontal crustal reflectors (Juhlin, 1988). The estimated thickness of the interpreted sill within our seismic volume, comparable to values cited here for mafic igneous sills, would not be expected to alone cause the large closed-contour magnetic anomaly of >600 nT in amplitude (Daniels et al., 2008).
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SUMMARY AND CONCLUSIONS

New 2D and 3D seismic data furnish an unprecedented view of reflectivity in Precambrian rocks of the EGRP beneath the Paleozoic Illinois Basin. The new coverage and the high resolution of the data reveal significant fine-scale features not previously possible with limited 2D data available. The results of our study extend observations of Precambrian seismic stratigraphic sequences from the southern Illinois Basin northward over a distance of 75 km. The basement seismic reflectors exhibit geometric properties of mafic igneous sill complexes by analogy with better constrained examples of sills from several locations (e.g., Rockall Trough, North Sea, Siljan Ring). We observe a discrete, bowl-shaped basement sequence, which corresponds to a prominent magnetic intensity anomaly, with dimensions of almost 30 km width and ~2.3 km maximum observed thickness. The thickness represents a minimum value, as the upper part of the sequence may have been beveled off by uplift and erosion. Apparent internal horizontal reflectivity appears copiously on the 3D sections, but is likely mostly or entirely multiple reflection. A less-well-defined series of bowl-shaped reflections is also seen deeper to the east. Three possible explanations may be proposed for the origin of the strong basement reflectivity. Our preferred explanation, that best fits the new profiles centered around Decatur, Illinois, is a complex of mafic igneous sills intruded into (or with the felsic igneous basement of the EGRP). Emplacement of such a bimodal igneous complex is consistent with crustal extension and provides further evidence of a major, but poorly understood, Proterozoic rifting and/or magmatic event in the central USA midcontinent.

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From our estimated area and thickness values, we have a conservatively estimated volume of 38.4 km³. These estimates are comparable to outcrop-based observations of diabase sills from many locations around the world. For example, the Great Whin Sill is reported to have thicknesses of as much as 100 m or greater (Goulty, 2005). Diabase sills within the Karoo Basin have maximum thicknesses of 100 m (Chevallier and Woodford, 1999) and 150 m (Galerne et al., 2011). The Ferrar igneous province of Antarctica has multiplied stacked diabase sills of ~300 m in thickness (Muirhead et al., 2012) and an estimated volume approaching 230,000 km³ (Elliot and Fleming, 2004; Muirhead et al., 2012). For a broad area of the San Rafael Swell of Utah (USA), Richardson et al. (2015, p. 2) measured diabase sill thicknesses between 5 and 40 m and estimated these to represent a “magma plumbing system in a tabular block approaching 25 km² in volume.” Thus, our conservative estimates of sill thickness, area, and volume are consistent with direct measurements from outcrop.

In the midwestern USA, subordinate mafic igneous sills and dikes have intruded into granitic country rock in the St. Francois Mountains (Ozark dome) in southeast Missouri (Kisvarsanyi and Kisvarsanyi, 1990; Walker et al., 2002). According to Van Schmus et al. (1996), mafic igneous plutonic rocks in the St. Francois Mountains are related to the main 1470 ± 30 Ma igneous event of the EGRP. These mafic igneous rocks were derived from the same source rocks that produced the dominant granites and rhyolites (Van Schmus et al., 1996). Our interpretation is that the relationship between the granitic and basaltic basement components of our study area is similar to that of the EGRP of the St. Francois Mountains. If correct, this suggests that the reflectors of our study area represent mafic igneous sills or plutons that are synchronous with the felsic igneous host rocks. Such bimodal volcanism is consistent with an interpretation of subduction along an active continental margin or lithospheric extension (Walker et al., 2002). Although igneous sills may form in any tectonic environment, major sills tend to be diabase and intrude in extensional tectonic environments (Kavanagh et al., 2006; Magee et al., 2015). As pointed out by Lidiak (1996), basalts encountered in deep boreholes further to the east (but not in Illinois) are interpreted to be associated with crustal rifting; however, although these basalts tend to be assigned a Keweenawan age, isotopic dates are not available, and the basalts could either be synchronous with or postdate the granitic basement.

A complicating factor is the geochemically defined boundary between older and younger Proterozoic lower crust, which divides the area of the Centralia Sequence in southern Illinois, southeast of the boundary, from our study area, northwest of the boundary (Fig. 11). According to Van Schmus et al. (1996), the portion of the EGRP situated northwest of the boundary formed from the remelting of ancient lower crust that formed before 1550 Ma. The primary age of the lower crust is younger southeast of the boundary (Van Schmus et al., 1998). This could mean that the reflectivity patterns (and thus the interpreted diabase intrusion) within Precambrian basement beneath our study area developed in (or from) crust that is older and possibly of different origin than that of the Centralia Sequence in southern Illinois.
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